describe the relationship between MFA and MOE for each of the provenances. Consequently, regression analysis was conducted and one equation was found to be sufficient to describe the relationship between MFA and MOE for all four provenances. This equation is as follows:

$$\textbf{MOE (N mm}^{-2}\textbf{) = 18519 – 606.1 (MFA°)}$$

Furthermore, the regression analysis showed that over 76% of the variation in MOE data could be attributed to MFA.

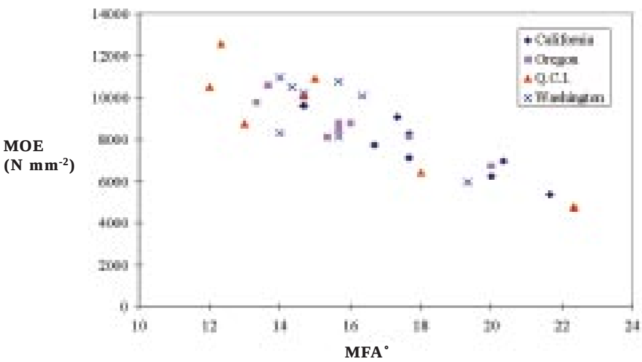

Figure 3. The relationship between MFA and MOE for each of the four provenances.

Fig. 4 shows the relationship between the MFA and the MOE data graphed with the best fitting line.

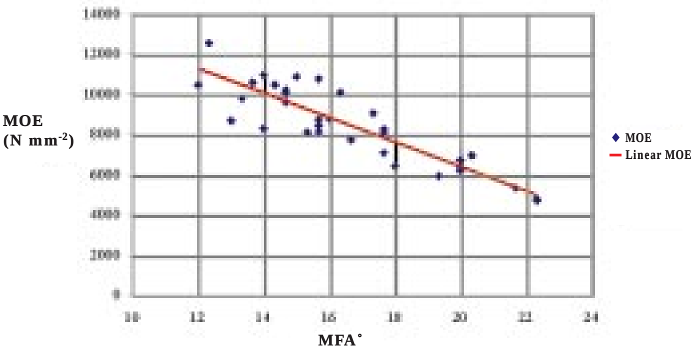

Figure 4. The relationship between MFA and MOE

Correlating MFA and MOR

A similar process was carried out to determine the relationship between MFA and MOR for each of the provenances. When the data was plotted there was little suggestion of the need for four separate equations, thus regression analysis was conducted. Statistical analysis of the three models regressed, confirmed that one equation was sufficient to describe the relationship between MFA and MOR for all four provenances. This equation is as follows:

$$\textbf{MOR = 113.2 – 2.8(MFA°)}$$

In this instance, the MFA only accounts for 34% of the variation in MOR. Figure 5 shows the relationship between the MFA and MOR data graphed with the best fitting line.

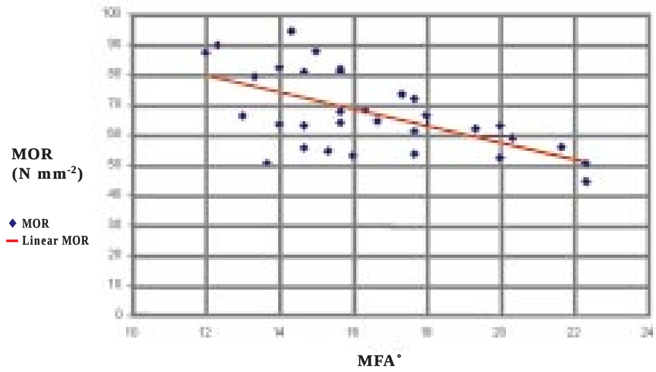

Figure 5. The relationship between MFA and MOR

Optical Density Data

Optical density readings were taken from each of the thirty two trees. The readings were taken from the first fourteen rings of the trees and then averaged to give an average reading per tree. Results are given in table 3.

Table 3: Mean optical density per provenance

Provenance	***Mean optical density(kg m^{-3})***	***SE***
California	532.7	24.1
Oregon	513.4	
Q.C.I.	573.1	
Washington	561.2	

Analysis of variance revealed significant differences between the mean optical density of the four provenances at the 10% level. Optical density readings were weighted by the cross section of the stem from which the samples came. Analysis of this data confirmed the outcomes for the optical density readings. Differences between the weighted density values per provenance were significant at the 10% level. For both the optical density readings and the weighted density values, a pairwise comparison of the means confirmed a significant difference between the Oregon and the Q.C.I. provenances.

Research Conclusions

The study confirmed the strong relationship between MFA and stiffness. When considering provenance selection based on stiffness or MOE, no selection preference can be given to any of the four provenances. However, preference can be given to the Washington provenance based on selection for MOR and to the Q.C.I. provenance based on selection for density.

When considering provenance selection based on MFA, the Californian provenance showed a significantly higher MFA in the juvenile wood. Based on this study alone, the Californian provenance should be avoided.

Wood quality may be assessed by using wood density as an indication of its strength and the microfibril angle (MFA) as an indicator of its stiffness. Little, if any, Irish research had examined the internal wood structure (density and MFA) of Sitka spruce from different provenances. In 1997 a COFORD funded project was initiated and focused on four different provenances (Fig. 1):

1 California (Crescent City)
2 Southern Oregon (Brookings)
3 Queen Charlotte Island (Copper Creek)
4 Southern Washington (Nasselle)

The study revealed little difference between the mean MFA for the four provenances. However, substantial differences were detected in MFA from pith to cambium, to the extent that MFA variation was greater within trees than between provenances. A single regression line was found to describe the relationship between MFA and MOE for all four provenances. The following is an outline of the research background and findings.[1]

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The Mechanical and Physical Wood Properties of a Range of Sitka spruce Provenances

Mary Treacy, Jos Evertsen and Áine Ní Dhubháin

Background

Sitka spruce currently occupies over 60% of the existing forest estate in Ireland and has a mean yield class of 16.5m^3 ha^{-1} yr^{-1}. With an average rotation length of forty five years and a number of end uses, the species has proven itself to be highly productive in the Irish environment. It is therefore important that the trees being planted produce high quality timber. This study examined the strength properties of four provenances of Sitka spruce grown in Ireland.

Wood Quality

It is generally accepted that the density of wood is an indication of its strength, while the microfibril angle of wood is an indicator of its stiffness. These two features - strength and stiffness - may be used to define wood quality.

Wood Density

The density of wood is quite a complex property affected by: the thickness of the cell walls; the diameter of cells; the chemical content of the wood and the ratio between earlywood and latewood. Not only does it impact upon the strength and processing behaviour of sawn wood, but it also affects the yield of wood fibre in pulp production i.e. a low density wood will have less strength and produce less wood fibre than a high density wood.

Variation in Wood Density

Density will vary with species, provenance, site location and within each tree depending on the point in the tree at which it is measured. The primary factor determining wood density is the width of the earlywood band. The faster a tree is growing the larger the earlywood bands per annual ring will be and thus the lower the density of the wood. In some species the lowest density will coincide with the zone of juvenile wood, which has few latewood cells and a high proportion of cells with thin cell walls. In trees that have grown fast over a short rotation the juvenile core will occupy a large proportion of the stem and such trees will have low wood density. In some species it has been observed that density will even decrease with height along the stem.

[1] *Extract from COFORD final report publication 'A comparison of mechanical and physical wood properties of a range of Sitka spruce provenances'*

Despite the variation in wood density, it remains a popular indicator of wood quality for two reasons. It is a very good indicator of wood strength – as wood density increases so too does strength. Also, wood density has shown to be highly heritable and thus very useful in tree breeding programmes.

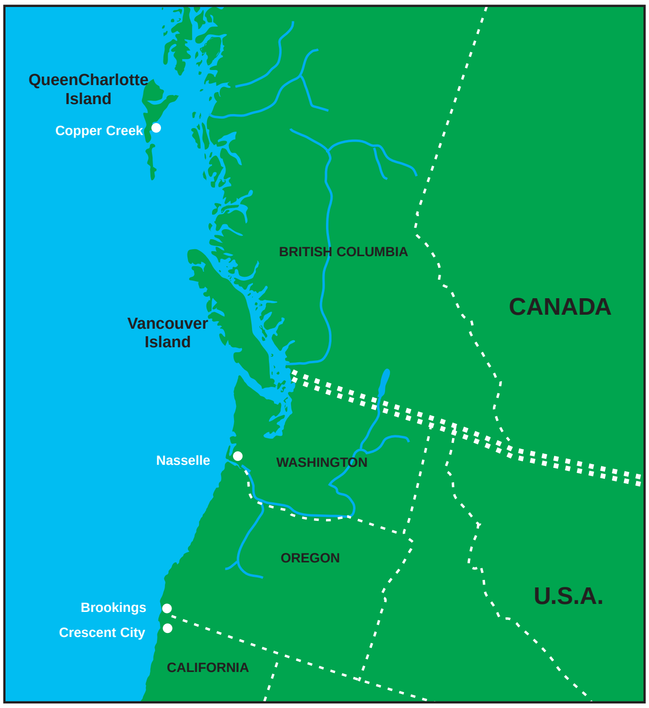

Figure1. Map showing range of Sitka spruce provenances tested.

Microfibril Angle

Microfibril angle is used as an indicator of wood stiffness, wood shrinkage and certain properties in paper. The amount of stiffness of a material is measured as its modulus of elasticity (MOE). It has been shown that wood stiffness is determined by the amount and distribution of cellulose within the cell wall. Thus, to examine microfibril angle we must look at wood at the cellular level. A young plant cell will form a thin, flexible wall called the primary wall. Outside the primary wall is the middle lamella which glues the cell to the other cells around it. On the inside of the primary wall the secondary wall is formed. The secondary wall consists of three layers and these are called S1, S2 and S3 (see Fig. 2). Cellulose is bundled together in the cell wall to form microfibrils which provide support and structure to the cell walls. Microfibrils will be aligned in a certain way, and it is the angle that the microfibrils make to the axis of the cell wall that is defined as the microfibril angle.

The effect of MFA on Wood Quality

The microfibril angle of the S2 layer in the tracheid[2] cell wall is recognised as one of the main determinants of the mechanical properties of wood, as well as having significant impact upon paper properties. It has been shown that:

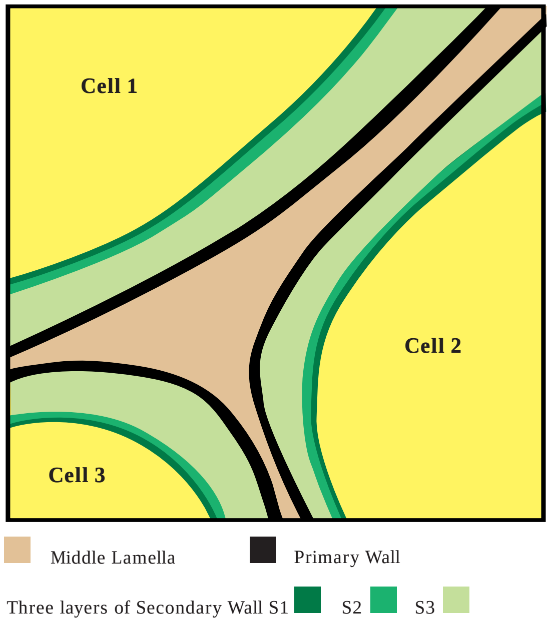

Figure 2. Diagram of plant cells and cell wall components

1. As MFA increases, wood stiffness decreases. For example, a decrease in MFA from 40˚ to 10˚ can bring about a five fold increase in stiffness;

2. Small MFA's are associated with high tensile strength in paper;

3. MFA is related to tracheid cell length. Longer tracheids have smaller microfibril angles;

4. Shrinkage in wood during the drying process is also governed to a large extent by MFA. Longitudinal shrinkage has been shown to be negligible when MFA is less than 30˚.

Variation in MFA

MFA varies from tree to tree, pith to cambium and with height in the stem. It will also vary with speed of growth of the tree. Very limited research worldwide has been carried out examining MFA variation among provenances, hence the significance of this research.

Study Objectives

Although there are various environmental reasons why a particular tree will grow faster than another, all other things being equal, the provenance of the trees will play a major role in determining growth rates. Little if any work has been carried out in Ireland to examine the internal structure of wood from different Sitka spruce provenances. Thus, in 1997, a COFORD funded research

[2]Tracheid cells are long thin cells with tapered ends. They are part of the main water transport system in a plant. However, because their secondary walls are hardened with lignin they operate in the structural support of the plant, as well as water transport.

project was initiated. The objectives of the project were clear:

1. To examine the variations in wood density, microfibril angle and the strength/stiffness ratio between four provenances of Irish grown Sitka spruce;
2. To seek relationships between MFA, wood strength and stiffness;
3. To provide information which might be useful in future tree breeding programmes to improve the quality of Irish grown Sitka spruce timber.

Selection of Trees

The trees were established in 1976 as part of a provenance trial examining forty eight different provenances of Sitka spruce. Sample plots of 0.01 ha were laid down and eight trees of mean DBH were selected from each of the four provenance plots. Edge trees were not included. Rings 2, 5, 10 and 14 from the pith were selected for sampling of microfibril angle.
(The methodology is outlined in full in the COFORD final report publication. *'A comparison of mechanical and physical wood properties of a range of Sitka spruce provenances'*).

Statistical Analysis

The MFA, MOE, modulus of rupture (MOR) and density were the main parameters measured in the study. (MOR is the maximum load a wood sample can sustain prior to rupture, while wood density is determined using optical density data). Statistical analysis was by split-plot design, with the provenance effect considered the main plot treatment and the rings within the trees considered the sub-plot treatment. All of the data were subject to analysis of variance tests to determine how these characteristics differed according to provenance.

Microfibril Angle Data

Two MFA measurements were taken per ring. The mean MFA values per ring for each provenance are presented in table 1.

Table 1: Mean MFA° per ring per provenance

Provenance	Ring				
	2	5	10	14	SE
California	22.0	24.7	20.6	11.7	0.69
Oregon	20.1	18.2	18.2	10.6	
Q.C.I.	20.9	18.7	16.7	11.4	
Washington	20.7	17.4	16.2	9.4	

Note SE = Standard error

In contrast to the other provenances the mean MFA was highest in ring 5 for the Californian provenance. In addition, in both ring 5 and ring 10 the MFA's for the Californian provenance were significantly greater than the MFA's for the other provenances.

Analysis of variance showed that:
• MFA differed significantly between provenances;
• MFA differed significantly between rings.
There was a significant interaction between ring and provenance with respect to MFA.

MOE Data

Twenty four MOE values were recorded from each provenance. An analysis of variance conducted on the MOE data, showed that there was no statistically significant difference between provenances.

MOR Data

Twenty four MOR values from each provenance were also recorded. Table 2 outlines the mean MOR values per provenance.

Table 2: Mean MOR per provenance

Provenance	Mean MOR (N mm^{-2})	SE
California	59.93	4.93
Oregon	65.56	
Q.C.I.	69.47	
Washington	70.21	

An analysis of variance of the MOR data confirmed that the differences in the mean MOR values for each provenance were not significant. However, results from a pairwise comparison of the four provenances means showed that the mean MOR of the Californian and the Washington provenances differed significantly from each other.

Correlating MFA and MOE

A key objective of this research was to determine the relationship between microfibril angle and modulus of elasticity and to establish whether this relationship was the same for all four provenances. To achieve this, one wood sample was taken from each of the eight trees per provenance i.e. 32 samples. The mean MFA and MOE were recorded for each sample. This data was then plotted as in fig. 3.
This graph suggested that it was not necessary to have four separate lines with different slopes and intercepts to