A comparison of mechanical and physical wood properties

of a range of Sitka spruce provenances

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Foreword

Sitka spruce currently accounts for 60% of the forest estate in Ireland. It has been the primary source of raw material for the thriving timber processing sector. This situation will continue for some time into the future. No other species has matched the productivity of Sitka spruce across the wide range of site types available for forestry in this country. Although the range of species being planted is now more diverse than ever, it remains imperative that the production of high quality timber continues to be one of the prime objectives of forestry.

Many provenance trials have been conducted over the years to try and identify the Sitka spruce provenance most suitable to Irish conditions. The focus was primarily on maximising timber volume. As we enter a period of increasing globalisation, with timber traded as an international commodity, it is vital that quality is not sacrificed in the drive for quantity. To this end, this COFORD funded study examined the strength properties of the four main provenances of Sitka spruce grown in Ireland.

I would like to take this opportunity to highlight the commitment and dedication of the research team involved in this project. The research team included: Ms Mary Treacy, University College Dublin, Principal researcher, Dr. Jos Evertsen, Enterprise Ireland, Project leader and Dr. Áine Ní Dhubháin, UCD research supervisor. Shay Keogh, John Conway, Michael McCourt and Paul Lyons from Enterprise Ireland. Dr. David Thompson, Coillte. Dr. John Connolly, Dr. Alan Carr, Prof. John Gardiner University College Dublin. Prof. Peka Saranpaa and Erkki Pessonnen from the Finnish Forest Research Institute, Metla, Vantaa, Finland. Prof. Timo Paakkari, Seppo Andersson and Ritva Serimaa of the Department of Physics, University of Helsinki, Finland.

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2 Summary

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is currently the most important forest tree species in Ireland, occupying over 60% of the forest estate. In light of its suitability under Irish climatic conditions, it will continue to be the main species planted and used by the processing sector. Given the increasing competition in the domestic and foreign timber markets, it is imperative that the Sitka spruce provenances being planted will produce timber of high quality.

To date, provenance work on Sitka spruce in Ireland has focused mainly on the growth rate and branching characteristics of provenances. Little, if any, work has been carried out in Ireland to examine and compare the microstructure of wood from Sitka spruce provenances. The objectives of this study were to examine the variation in microfibril angle (MFA), density and strength/stiffness between provenances of Irish grown Sitka spruce. A further objective was to examine the relationship between MFA and wood strength and stiffness and to provide information which might be used in future tree breeding programmes to improve the quality of Irish grown Sitka spruce timber.

Four provenances were chosen for sampling (Washington, Queen Charlotte Island, Oregon and California). Eight trees were selected from each of these four provenances and from each of these thirty-two chosen trees, measurements of MFA, density and strength/stiffness were made and recorded. All of the samples for measurement were taken from the north east cardinal point of each of the trees and at a height straddling breast height. The MFA measurements were taken from the same four annual rings in each of the trees.

The results showed that the MFA varied significantly between provenances and annual rings. The highest MFAs occurred close to the pith for all provenances, with the exception of the Californian provenance whose MFA peaked in ring five. The lowest MFAs occurred in ring fourteen from the pith for all of the four provenances. The results also showed that optical wood density in the Oregon provenance was significantly less than the optical wood density in the Queen Charlotte Island provenance. Wood stiffness did not differ significantly between provenances. A strong negative linear relationship was found between MFA and wood stiffness. This relationship was found to be the same for all provenances. Wood strength varied significantly between the Californian and Washington provenances only. A linear relationship was also found between MFA and strength. This relationship was the same for the four provenances examined.

Because of the strong linear relationship between MFA and wood stiffness, it is suggested that future wood quality improvement programmes focus on selecting trees on the basis of MFA rather than density.

3 Introduction

Introduced in Ireland in the 1830's, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) accounts for over 60% of the forest estate. Sitka spruce grows best on wet mineral soils but has produced excellent yields on poor soils including peats (Anon, 1995a). Grown in Ireland, the species has a mean yield class of 16.5$m^3 ha^{-1} an^{-1}$ and an average rotation length of 45 years (Williamson and Nieuwenhuis, 1994). As Sitka spruce has proved to be such a highly versatile and productive species, it is likely to remain the principal forest species in Ireland.

The timber of Sitka spruce is suitable for a wide variety of end-uses such as structural timber, fencing, palletwood and pulpwood and is the mainstay of the current wood processing industry (Anon, 1996). Strength properties are likely to be reduced by any practice encouraging faster growth and shorter rotations, which are liable to produce a larger core of lower density juvenile wood (Mitchell and Denne, 1997). The fast growth rate attained by Sitka spruce in this country, has meant that its timber has not quite matched the quality of timber from other conifers e.g. Norway spruce (*Picea abies* (L.) Karsten) and Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) and the species is not generally suitable for use as a finishing timber for interior applications (Anon, 1996).

In the past, Sitka spruce seed from the Queen Charlotte Islands (Q.C.I.), off the west coast of Canada was the most widely planted provenance in Ireland. This provenance was chosen mainly because of its similar latitude to Ireland and the belief that it offered increased protection against frost damage (Thompson, 1995a). However, this view has changed somewhat in the past few years, with the realisation that no real protection from late spring frosts was being offered. Irish foresters are now moving increasingly towards planting mid Oregon and southern Washington provenances. This move is due mainly to the greater productive potential of these provenances over the more northerly provenances (Thompson, 1995a).

Provenance work to date on Sitka spruce has concentrated mainly on improving phenotypic (external) features e.g. faster growth rate, lighter branching, straighter stems and taller trees. Little, if any, work has been carried out in this country to examine the microstructure of Sitka spruce, to determine if any differences/interactions exist between factors such as density, strength and microfibril angle. Similarly, the impact that the inter-relationship of these features has on wood quality has not been assessed. This project was undertaken with the following objectives:

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

4 Literature Review

4.1 PROVENANCE TRIALS IN IRELAND

Eleven coniferous species and six broadleaved species have been planted in provenance trials in various locations throughout Ireland. Information on the performance of Sitka spruce provenances in Ireland comes from two main series of experiments. The first was established in 1960 in Killarney forest and is one of a series of fifteen trials testing ten provenances throughout Britain and Ireland. The second, the IUFRO collection, was established in 1975 on sixteen sites testing sixty seven provenances. These provenance trials have shown that provenance differences arise mostly in growth rate and time of dormancy, and that these traits are under strong genetic control. Differences in wood characteristics and branching habit are small between provenances and are affected more by site and silvicultural treatment than by genetics. Pfeifer (1991) concluded that opportunities for genetic improvement through provenance selection were mainly in maximising wood production and quality and minimising climatic damage.

4.2 WOOD QUALITY

Wood quality can be defined in terms of attributes that make it valuable for a given end use (Jozsa and Middleton, 1994). In general, density and microfibril angle (indicators of strength and stiffness respectively) are reputed to be the key determinants of wood quality. For the sawmiller, wood quality is reflected in the value of mill production and depends on grade out-turn and the value for each grade (Addis Tsehaye et al., 1995a). Wood quality for the structural engineer means wood with a high stiffness level, an attribute which is most important for beams, joists and purlins. Strong wood is required for studs and trusses (Addis Tsehaye et al., 1995a). For the wood technologist, wood density is important, as an increase in its value can result in higher timber strength and a greater yield of pulp (Elliot, 1970). The paper and pulp mill requirements for quality wood are long fibre length with low lignin content (Zobel and Van Buijtenen, 1989). A minimum fibre length of 2 mm is necessary to produce acceptable Kraft pulp and a reduction in lignin content leads to a considerable savings during the production of bleached Kraft pulp (Walker and Butterfield, 1996). The two most important wood parameters for Kraft pulping are basic density and tracheid length (Cown and Kibblewhite, 1980).

4.3 WOOD DENSITY

Wood density and wood specific gravity both indicate the amount of actual wood substance present in a unit volume of wood (Zobel and Jett, 1995). Wood density is not a simple characteristic. It is affected by the cell wall thickness, the cell diameter, the earlywood to latewood ratio and the chemical content of the wood (Cave and Walker, 1994).

4.3.1 Impact of density on wood quality

Wood density is an important wood property for both solid wood and fibre products in both conifers and hardwoods (de Guth, 1980). Panshin and de Zeeuw (1980) reported that density is a general indicator of

cell size and is a good predictor of strength, stiffness, ease of drying, machining, hardness and various paper making properties. Brazier and Howell (1979) also expressed the opinion that density is one of the most important properties influencing the use of a timber. They emphasised that it affects the technical performance of wood and in particular the strength and processing behaviour of sawn wood and veneer, and the yields of wood fibre in pulp production. Philips (1941) reported that wood density is a measure of the cell wall material per unit volume and as such gives a very good indication of the strength properties and expected pulp yields of timber. Basic density is closely related to end-use quality parameters such as pulp yield and structural timber strength (Harvald and Olesen, 1987). Cown (1992) reported that the density of wood is recognised as the key factor influencing wood strength. Indeed according to Schniewind (1989) much of the variation in wood strength, both between and within species, can be attributed to differences in wood density. Research has shown that higher density species tend to have stronger timber than lower density species (Addis Tsehaye et al., 1995b; Walker and Butterfield, 1996).

4.3.2 Density variations within a tree

Density within a tree varies from pith to bark and with height in the stem. Wood density varies from earlywood tissue to latewood tissue within each annual ring. Latewood tissue is composed of cells of relatively small radial diameter with a thick wall and a small lumen and therefore, has a higher density than thin walled earlywood cells with a larger cell lumen (Haygreen and Bowyer, 1996). There is general agreement amongst researchers that the primary factor influencing the density of wood is the width of the earlywood band laid down within any one annual ring (O'Sullivan, 1976). Indeed in many conifers, the basic density of the latewood zone is more than twice that of earlywood, thus, any increase in the proportion of latewood inevitably leads to an increase in whole ring basic density (Ward, 1975; Elliot 1970). Frequently, the relative densities of the earlywood and latewood within a tree are strongly correlated (Gladstone et al., 1970). Usually a tree with high-density earlywood will also have high-density latewood (Zobel and Jett, 1995).

Some species exhibit greater density variation than others. In Sitka spruce density is very high in the innermost rings and then decreases from the pith outward until a minimum is reached about rings 8 to 12, after which it rises gradually towards the bark (Harvald and Olesen, 1987). This is in agreement with Petty et al. (1990) who also found density in Sitka spruce to be relatively high near the pith, falling to a minimum further out and then gradually increasing with distance from the pith. This trend in wood density variation was also found for Norway spruce. The lower densities found in the inner twelve rings coincide with the juvenile wood zone. Density in this juvenile wood zone is low because there are relatively few latewood cells and a high proportion of cells have thin wall layers (Haygreen and Bowyer, 1996).

Density increases by up to 50% from the pith outwards and is reflected in an increase in the thickness of the S2 layer of the cell walls (see section 4.4). Thus, in moving outward from the pith, the wood mass increases (Walker and Butterfield, 1996). Donaldson et al. (1995) found that ring density for Monterey pine (*Pinus radiata* D. Don) changed from approximately ring 10 outwards, with increases in both earlywood and latewood density, as well as an increase in the amount of latewood.

In a study carried out by Harvald and Olesen (1987) on the variation of basic density within the juvenile wood of Sitka spruce, it was found that basic density decreased with increasing height in the stem.

Donaldson et al. (1995) reported a similar trend in Monterey pine grown in New Zealand. Simpson and Denne (1997) found that for comparable ring numbers, wood density was slightly greater at breast height than higher up in the tree. A similar pattern was noted by Harvald and Olesen (1987). Mitchell and Denne (1997) attributed this trend in density to the thicker tracheid walls that are found at breast height, than higher in the stem. However, in contrast, Ward (1975) found that for spruce species, density does not markedly decrease with height in the stem, but rather may even increase with increasing height.

4.3.3 Density variation between species and provenances

Each tree species has its own characteristic wood density (O'Sullivan, 1976). Density variation between species is basically due to differences in anatomical structure. Species differ with regard to cell types and the distribution of these cells within the wood. In addition, differences in the concentration of extractives and the chemical composition of cell walls may influence density. It should be noted, however, that woods of different species do not always differ in density (Tsoumis, 1992). Spruce species in general are considered to be low-density species. British grown Sitka spruce is estimated to have an average density of between 380-450 kg m^{-3} (Savill, 1992).

Wood density can vary among provenances and is very variable among trees and within individual trees of a given provenance (Zobel and Van Buijtenen, 1989). The faster growing more southerly Sitka spruce provenances produce timber which is less dense than that from the slower growing more northerly provenances. Jeffers (1959) concluded that Sitka spruce of Canadian origin (Q.C.I.) had significantly greater wood density than Sitka spruce of American origin (Washington, Oregon and California). In agreement, Murphy and Pfeifer (1990) reported a trend toward lower wood density with more southerly provenances.

4.3.4 Environmental impacts on density

Wood density is influenced by the environment, which determines the rate of tree growth. The density of Sitka spruce wood is known to decrease in response to increased growth rate (Savill and Sandels, 1983). This decrease in density has been recorded in the juvenile wood of fast grown Sitka spruce. Mitchell and Denne (1997) found that on sites where Sitka spruce stands were fast growing, wood density decreased more rapidly across the juvenile wood, down to a lower minimum value, than on sites where Sitka spruce stands were slower growing. In fast grown Sitka spruce lower density was recorded for mature wood sections. Growth rate also influences the extent of the juvenile core and the proportion of stem it comprises. In fast grown trees cultivated on a short rotation, a larger proportion of the stem will comprise juvenile wood. Trees from shorter rotations have lower densities because the proportion of low-density juvenile wood is higher (Zobel and Jett, 1995).

4.3.5 Heritability of density

Heritability is defined as the fraction of the phenotypic variation in any trait that is due to genetic differences as opposed to environmental effects on individuals. The expression of heritability is a site specific as well as a population specific parameter (Ayala and Kiger, 1984). Research has shown that density is a highly heritable characteristic. Cown et al. (1992) reported a narrow sense heritability (h2) of 0.9-1.0 for wood density. In addition several important factors influencing wood density i.e. latewood percentage (Zobel, 1961), cell wall thickness and cell diameter (Goggans, 1962) have been shown to be under genetic control. Zobel and Jett (1995) reported that typically, wood density is strongly inherited

and variable, thus enabling good gains from genetic manipulation. In breeding trials for density most researchers concentrate on juvenile wood. Frequently it is desirable to breed for high density to offset the high proportion of low density juvenile wood harvested from stands grown over short rotations (Zobel and Jett, 1995).

4.3.6 Density and strength

Wood is highly anisotropic in its strength properties i.e. it has different properties in longitdinal and tangential directions. This is due to its cellular structure and the physical organisation of the cellulose chain molecules within the cell walls (Schniewind, 1989). The existence of a linear relationship between wood density and strength has been demonstrated by several investigators (O'Sullivan, 1976). Similarly, it has been found that within the range of specific gravity found in most species, an approximately linear relationship exists between strength and specific gravity. Thus, Mitchell (1963) reported that a 0.02 change in specific gravity represents a change of about 70 kg cm^{-2} in the modulus of rupture of clear wood. On the other hand the relationship between specific gravity and stiffness (modulus of elasticity) is poor (Anon, 1980). Cave and Walker (1994) also found that density was a poor indicator of cell wall stiffness.

4.3.7 Measurement of wood density

Radiation densitometry is a commonly used technique for assessing density characteristics of wood samples. Direct measurement of the intensity of the radiation passing through the sample enables wood density variations to be recorded automatically (Cown and Clement, 1983). X-ray densitometry is used to give an optical radiographic reading of wood density but does not give an actual reading value. Other methods of measuring wood density include the water immersion method. This method determines the volume of the wood sample by measuring its buoyancy i. e. the difference between the absolute weight of the specimen and its weight when submerged in water. This method is also known as the direct method. Another water-based method involves soaking the wood samples before immersion in water. This method determines the volume of the wood sample by measuring the increase in weight of a container of water when the wood sample is submerged in it. A variation of this method involves using mercury instead of water as the displacement medium (O'Sullivan, 1976). There is also an oven-dry method. In using this method a 25 mm cross section is cut and oven-dried at 103 °C ± 2 °C until a weight equilibrium is achieved. The volume of the cross section is determined from physical dimension measurements (Evertsen, 1988).

4.4 MICROFIBRILS

The walls of wood cells are made up of the primary wall and the secondary wall. The secondary wall is composed of three layers, S1, S2 and S3. The S1 layer is the layer closest to the middle lamella, while the S3 layer is the layer closest to the cell lumen. The walls of wood cells are made up of three main substances. These are cellulose, hemicellulose and lignin (Butterfield and Meylan, 1980). Cellulose is laid down in the cell walls in the form of microfibrils (Haygreen and Bowyer, 1996; Walker, 1993). Of the three layers in the secondary cell wall, the S2 layer is the thickest and therefore, the most important (Tsoumis, 1992). Haygreen and Bowyer (1996) also reported that because the S2 layer is much thicker than the S1 or S3 layers, it has the greatest effect on how the cell behaves.

Microfibrils are the structural units of plant cell walls. Each microfibril contains a number of cellulose chain molecules bundled together, and is surrounded by low molecular weight hemicelluloses (Tsoumis,

1992). The hemicelluloses act as connecting agents that link or bond the microfibrils together (Haygreen and Bowyer, 1996). The cellulose chain molecules are generally arranged lengthways with regard to the microfibril axis, but run parallel to each other in portions. These portions are called crystalline regions. The molecules in these regions are strongly connected to each other by hydrogen bonding. The crystalline regions are followed by amorphous regions in which the cellulose molecules have no definite arrangement. The transition from crystalline to amorphous region is gradual. Approximately two thirds of the cellulose in the cell wall is crystalline in form while one third is amorphous (Tsoumis, 1992). Microfibrils vary in width from 1 μm in the primary walls to 10 μm in the secondary walls (Zobel and Jett, 1995). The angle that the cellulose microfibrils make to the axis of the cell wall is known as the microfibril angle. Microfibrils are present in each of the cell wall layers (Butterfield and Meylan, 1980).

4.4.1 Impact of microfibril angle on wood quality

The microfibril angle (MFA) of the S2 layer in the tracheid cell wall is known to be one of the main determinants of the mechanical properties of wood, including the modulus of elasticity (MOE), and shrinkage anisotropy (longitudinal and tangential shrinkage) (Donaldson, 1996). Watson and Dadswell (1964) reported that the microfibril angle also had a significant impact on paper properties. Small microfibril angles were associated with high tensile strength in paper, while large microfibril angles were associated with larger stretch and tear indices. The microfibril angle is known to be inversely related to tracheid length, with longer tracheids having smaller angles (Donaldson, 1993).

4.4.2 MFA and wood stiffness

The stiffness of wood arises from its cellulose content and the way that this cellulose is distributed within the cell wall (Cave and Walker, 1994). Walker and Butterfield (1996) reported that the microfibril angle has a very strong influence on the stiffness of wood. In agreement with this, Cave and Walker (1994) reported that the only known physical characteristic of wood capable of effecting large changes in the stiffness of wood is the cellulose microfibril angle in the S2 layer of the tracheid cell wall. Meylan and Probine (1969) also reported that the microfibril angle in the S2 layer of the tracheid cell wall is a principal predictor of timber quality, with density behaving as an additional variable.

In an experiment carried out by Cowdrey and Preston (1966) a six-fold increase in stiffness in the earlywood of Sitka spruce was observed as the microfibril angle decreased from 40° to 10°. In close agreement with this Walker and Butterfield (1996) observed that the stiffness of earlywood in Radiata pine increased five-fold as the microfibril angle decreased from 40° to 10°.

4.4.3 MFA and shrinkage of wood

The shrinkage of wood is governed to a large extent by its anatomical structure and by the orientation of the microfibrils in the cell walls (Harris and Meylan, 1965). When water enters the cell wall it occupies spaces between the microfibrils, so if the microfibril angle is large there is more swelling along the grain as water is added (Donaldson and Frankland, 1997). The reverse applies as water is removed from woody cells. In agreement with this Ying et al. (1994) reported that specific gravity and microfibril angle are the best predictors of longitudinal shrinkage in wood.

Walker and Butterfield (1996) reported that longitudinal shrinkage increased with microfibril angle but in a highly non-linear manner and was responsible for some degrade on drying. Harris and Meylan (1965) found that the general relationship between longitudinal shrinkage and MFA was curvilinear and

that the longitudinal shrinkage tended to be large when the microfibril angles were large and negligible when the microfibril angle was less than about 28°. In close agreement with this, Meylan (1968) reported that longitudinal shrinkage was negligible when the microfibril angle was less than 30°, but as the angle increased above this there was a very rapid increase in the longitudinal shrinkage and a corresponding decrease in tangential shrinkage. Meylan (1968) also found that high longitudinal shrinkage was often associated with short fibered wood of low density and strength. Indeed Harris and Meylan (1965) concluded that shrinkage of wood may be minimised by selecting for microfibril angles between 15° and 25°.

4.4.4 MFA and density / strength

Harris and Meylan (1965) and Walker and Butterfield (1996) found that wood density and tracheid length varied independently between trees. As a result, a strong correlation between wood density and microfibril angle, or wood density and strength should not be expected. At the same time, microfibril angle is known to interact with density (Wimmer, 1992) and may also interact with spiral grain, to influence the strength and stiffness of clear wood (Donaldson and Burdon, 1995). The shorter cell lengths observed in fast grown conifers imply lower tensile strength (Senft et al., 1985).

4.4.5 Variation in MFA

Variations in wood quality of any species can be attributed to variation within a tree, between trees in a particular stand, between different growing sites and between different silvicultural regimes (Addis Tsehaye et al., 1995b). Microfibril angle varies from pith to bark, with height in the stem, and among trees. The microfibril angle in the cell wall is affected by the size of the cell, with shorter and wider cells having larger angles (Tsoumis, 1992).

4.4.5.1 MFA variations within a tree

Microfibril angles vary within each growth ring. Cave and Walker (1994) reported that the MFA decreases from the first earlywood cell to the last latewood cell. Harris and Meylan (1965) also reported that the microfibril angle was larger in the earlywood cells than in the latewood cells.

The MFA is at its largest near the pith and gradually declines from the pith to the cambium (Walker and Butterfield, 1996; Phillips, 1941). Donaldson (1993) and Pedini (1992) both reported that the largest MFAs occur in the first five to ten growth rings from the pith. The MFA also decreases with height in the stem (Walker and Butterfield, 1996; Donaldson, 1992). In agreement with this Pedini (1992) observed a decline in microfibril angle within a ring with height in Sitka spruce. However, Addis Tsehaye et al. (1995a) reported that wood stiffness in Monterey pine increased from the pith to the outerpart of the log but was relatively constant up the height of the tree. Similarly, Walker and Butterfield (1996) noted that the stiffness of the cell wall increases from the pith to the cambium as the MFA decreases. The MFA is also larger in compression wood than in normal wood (Philips, 1941).

4.4.5.2 MFA variation between provenances

Microfibril angles have been the subject of much study but very little of this has been genetic research (Zobel and Jett, 1995). Although the variation in MFA from tree to tree appears to be genetically controlled, the degree of inheritance is not well known (Zobel and Jett, 1995). There is limited research world wide into microfibril angle variations among provenances. In New Zealand some work has been carried out on a number of Monterey pine clones. In a trial carried out by Donaldson and Burdon (1995) on a small number of Monterey pine clones, it was concluded that there was a significant genetic component to the variation in microfibril angle.

4.4.5.3 Environmental impacts on MFA

Growth rate influences microfibril angle in two ways. Firstly, fast growing trees have the largest microfibril angles both in juvenile and mature wood, and secondly, narrow growth rings are formed in some trees when they are suppressed and these rings tend to have tracheids with a large MFA (Pedini, 1992). The results of a trial carried out by Pedini (1992) suggest that fast growth may lower the quality of juvenile wood in Sitka spruce. Herman et al. (1999) reported that in a comparison of slow-grown versus fast-grown Norway spruce, a significant increase of the S2 microfibril angle was demonstrated in the fast grown spruce. This may change the quality of wood as well as the strength properties of pulp and paper produced from it.

4.4.6 Heritability of MFA

Donaldson and Burdon (1995) reported that both stiffness and MFA have a significant genetic component to their variation. Cave and Walker (1994) reported that there appears to be sufficient variation in microfibril angle between trees to justify selection of clones to yield stiffer timber. Meylan and Probine (1969) suggest that breeding is necessary to improve microfibril angle. Mergen and Furnival (1960) found that the microfibril angle was under some genetic control in the hybrid between Japanese black pine (*Pinus thunbergii* Parl.) and Japanese red pine (*Pinus densiflora* Sieb. and Zucc.).

4.4.7 Measurement of microfibril angle

There are essentially three methods for measuring MFA in the cell walls: X-ray diffraction (Cave, 1966; Boyd 1977), polarised light (Page, 1969; Leney, 1981), and direct or indirect observation (Cockrell, 1974; Senft and Bendtsen 1985).

X-ray diffraction is the fastest and most modern method of measuring the microfibril angle. This method enables large sample numbers to be measured in a short time, but the interpretation of the results requires considerable expertise. X-ray diffraction cannot be applied to pulp fibres because of the technical difficulty in obtaining a highly oriented sample (Donaldson, 1991). X-ray diffraction gives an indirect evaluation of the microfibril angle from which an estimate of the microfibril angle can be determined.

The polarised light method of measuring MFA is very time consuming. This microscope-operated method allows for the fibril direction in a portion of the cell wall to be readily obtained by examination between crossed polars. Upon rotation of the specimen the transmitted light intensity falls to zero when the microfibrils are parallel to one of the polars. However, this procedure cannot be used for intact fibres as the opposite sides of a helically wound cell wall interfere (Leney, 1981). This latter problem can be overcome by observation of the extinction of polarised light by a single wall as observed through a bordered pit. The polarised light method assumes that extinction occurs when the microfibrils in the S2 layer are parallel to the polariser. This is only strictly true, however, if the thickness of both the S1 and S3 layers are zero. It has been assumed in previous work that the S1 and S3 layers are sufficiently thin to have a negligible effect on the determination of the fibril angle (El-Hosseiny and Page, 1973).

The direct and indirect observations include the method of Cockrell (1974) which involves measuring the orientation of pit apertures in latewood tracheids which follow the microfibril angle of the S2 layer of the secondary wall. The technique of Senft and Bendtsen (1985) involves inducing checking in the cell wall. Checking also tends to follow the microfibril angle. A 2% solution of iodine-potassium iodide is

then precipitated within the checks and the MFA is measured. According to Senft and Bendtsen (1985), it is possible to measure all three layers of the secondary wall by selective focusing of the microscope.

4.5 SELECTION FOR IMPROVING WOOD QUALITY

In the past, selection for wood quality was based mainly on density but increasingly emphasis is being placed on the importance of the microfibril angle.

4.5.1 Selection for wood quality on the basis of density

Selection according to density does not appear to be a very effective method for identifying better structural timber (Walker and Butterfield, 1996). This is in accordance with other researchers in New Zealand who have concluded that the quality of structural timber could be significantly improved if trees were selected on the basis of wood stiffness rather than wood density (Walker and Butterfield, 1996; Addis Tsehaye et al., 1995a; Cave and Walker, 1994). Rather than focusing on the quantity of matter in a piece of wood (its density), the quality of material in the cell wall should also be considered (Cave and Walker, 1994). Research carried out by Addis Tsehaye et al. (1995a) showed that a 10% increase in wood density only increased wood stiffness and strength by about 10%. Cave and Walker (1994) also reported that density is a poor indicator of cell wall stiffness, and that although selection on the basis of density would provide some gains, these were unlikely to be as great as those achievable by selection for microfibril angle itself.

4.5.2 Selection for wood quality on the basis of MFA

The impact of MFA on wood stiffness is becoming increasingly important, due to the emphasis, throughout the world, on fast growing, short rotation, plantation forestry. The amount of juvenile wood being harvested will increase and it is within this wood, that the microfibril angle is greatest and the wood least stiff (Cave and Walker, 1994: Zobel and Jett, 1995). Selection on the basis of MFA results in superior wood stiffness, which in turn results in an improved structural grade out-turn (Walker and Butterfield, 1996). Based on the relationship between microfibril angle and stiffness given by Cave (1968), a reduction in juvenile wood microfibril angle by an average of 10° could increase stiffness of juvenile wood at comparable density by a factor of 1.6-2.0 (Donaldson, 1996). As with density it should be possible to select on the basis of microfibril angle at a very early age as the microfibril angle always decreases with age (Walker and Butterfield, 1996). Microfibril angle plays a major role in determining the stiffness of juvenile wood in fast grown pine plantations (Cave and Walker, 1994). The variation in microfibril angle among trees suggests that there is potential for selection of low microfibril angle to improve wood quality (Donaldson, 1992). With microfibril angle there is more variation in juvenile wood than in mature wood characteristics, and the greatest benefit would undoubtedly be achieved by improving juvenile wood regardless of the rotation age (Walker and Butterfield, 1996).

5 Materials and methods

5.1 INTRODUCTION

The trees selected for this study were from Shillelagh forest, in south Co. Wicklow, owned by Coillte. This forest was previously part of Coolatin estate and was planted with Scots pine (*Pinus sylvestris* L.) and Larch (*Larix decidua*) in the early part of the 20th century. This crop failed and the area was prematurely clearfelled between 1964 and 1966. In 1976 the site was selected as a provenance trial site for Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Forty-eight provenance plots were laid down for provenances from Washington, Oregon, California, Alaska and British Columbia including Queen Charlotte Islands (Q.C.I.). The aims of this provenance trial were as follows:

(a) To provide a source of material for future breeding programmes;
(b) To provide plots larger than those established in the 1975 IUFRO Sitka spruce provenance experiments (Thompson, 1995b). (The IUFRO experiments were established in 1975 on sixteen sites testing sixty seven sources (Pfeifer, 1991)).

The wood microstructure of four selected provenances was studied, i.e. California (Crescent City), Southern Oregon (Brookings), Q.C.I. (Copper Creek) and Southern Washington (Nasselle).

5.2 DESCRIPTION OF SITE

The geology of the site is Ordovician. The soil type is a brown podzolic, with good drainage. The site has a moderate to severe slope and is north facing. The elevation of the site ranges between 180 m and 230 m. Prior to planting, the site was prepared with a Clarke plough. The ploughing proceeded west to east along the contour. The main vegetation at the time of planting was bracken, grasses, briar and wood rush.

5.3 LAYOUT OF PROVENANCE STANDS

The provenance trial was established in the spring of 1976. One plot was laid down for each of the forty eight provenances. Each plot was a minimum of 20 m wide, while the length varied according to the availability of plants. Within these plots, transplants (1+3) were planted at 2 m x 2 m spacing on the side of the ploughed furrow. Each plot corner was permanently staked and labelled.

5.4 HISTORY OF SELECTED PROVENANCE STANDS

The performance of the four selected provenances was examined in 1992. A variety of crop parameters were measured and these are shown in table 5.1.

Table 5.1 - Performance of four selected origins of Sitka spruce in the Shillelagh gene bank

Region	Provenance	Mean top height (m)	Mean dbh (cm)	Dbh Range (cm)	Vol/Ha (m^3)	Yield Class ($m^3ha^{-1}yr^{-1}$)
California	Crescent City	13.00	15.7	10 - 18	321.8	26/28
Oregon	Brookings	14.25	16.5	7 - 24	379.8	26/28
Q.C.I.	Copper Creek	8.25	14.4	9 - 19	184.5	20
Washington	Nasselle	10.75	15.5	8 -24	213.5	24

Source: Thompson, 1995b.

The Californian and Oregon provenances exhibited the greatest growth rates achieving yield classes of 26/28. The Q.C.I. provenance had the slowest growth rate achieving only yield class 20.

In 1996 a number of trees from each of the four selected provenances were felled in order to study the wood microstructure of the trees. The trees in the provenance stands had not received a thinning prior to this wood quality sampling.

5.5 SELECTION OF SAMPLE TREES WITHIN EACH PROVENANCE STAND

Eight trees were selected from each of the four provenances. A 10 m x 10 m plot (0.01 ha) was laid down in each of the four-selected provenance stands. Edge trees were not included in the plots and a distance of at least two rows of trees back from the stand edge was maintained. In general the 0.01 ha plots were located as close to the roadside as possible to allow for easy extraction. The dbh of all the trees within each of the four plots was then measured and recorded. This gave the plot dbh distribution and the mean dbh. Eight trees of mean dbh were then selected at random from each of the four 0.01 ha plots. The selected trees were marked at breast height on the southwest cardinal point (determined with a compass) and then felled.

5.6 SAMPLING OF TREES

After felling, the thirty two trees were cut to commercially sized logs of 5 m in length (Figure 5.1A). From each of these logs a 1 m long section was cut at a level straddling breast height, in such a way as to have breast height as close to the mid point of the 1 m section as possible (Figure 5.1B). From this 1 m section a disc approximately 50 cm high was cut from the largest internodal area clear of knots, located either on or immediately above or below the breast height marking (Figure 5.1C). This disc was used for all wood quality sampling tests.

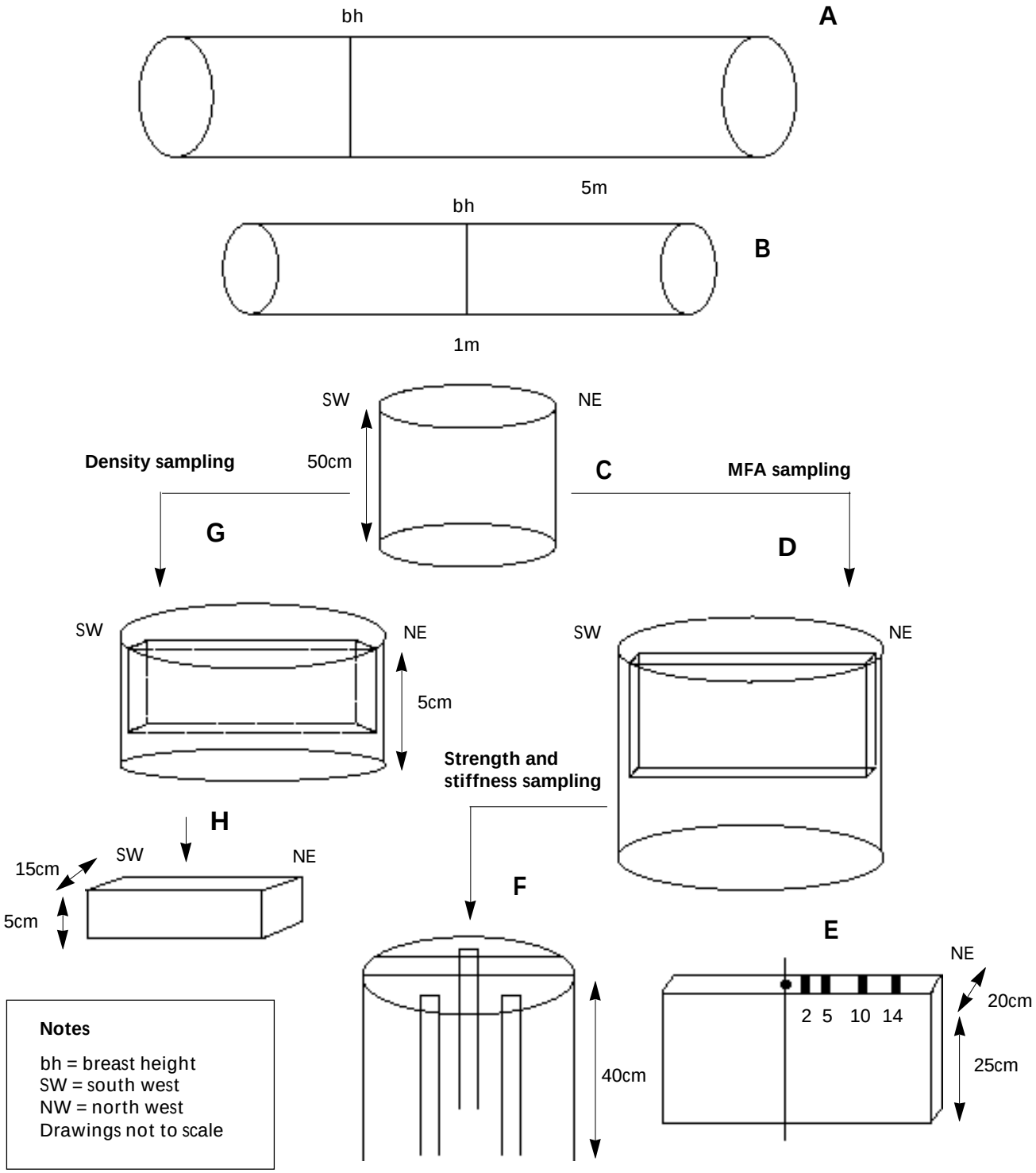
5.6.1 MFA sampling method

A disc roughly 40 cm high (Figure 5.1D) was cut from the 50 cm sample disc described in section 5.6. A core (radial) section, from north-east to south-west was taken from this 40 cm disc. A slice approximately 25 mm high was cut from this section. This slice was then cut to approximately 20 mm in width (Figure 5.1E). The slice was then split along the pith, separating the north-east side from the south-west side. To reduce variation in the sample it was decided that all samples would be chosen from one side of the tree and for this reason the samples were taken from the north-east side of the tree only.

Rings were then selected for microfibril angle sampling and included rings 2, 5, 10 and 14 from the pith (Figure 5.1E). These rings were chosen to give an indication of the changing trend in microfibril angle

across the radius of a tree. Thus, on the slice described earlier the selected rings were marked and their distance from the pith was measured. The slice was then split at each of the marked rings and each of these slice sub-sections was clearly labelled. A small piece of wood (i.e. matchstick sized) was then cut from the earlywood section only of each of the marked rings. This matchstick sample was used for the microfibril angle measurements.

FIGURE 5.1 Sampling methodology



5.6.2 MFA sampling intensity

To determine the number of samples of microfibril angle that were needed per ring, a pilot study was conducted. Initially it was intended to take one hundred estimates of MFA per sample ring. This was the approach used by the Forest Research Institute in Finland (Saranpaa et al., 1997). Thus, when one hundred estimates of MFA were taken from a selection of the rings from a sample of trees, the data were analysed. The structure of the pilot data set, which consisted of 1,800 MFA estimates was as follows. Readings were taken from six trees (two trees were sampled from both California and Washington, and one tree was sampled from both Oregon and Q.C.I.). From each tree, three rings (2, 5, and 10) were sampled and within each ring one hundred estimates of MFA were taken. This subset of 1,800 data readings was analysed. Following a review of the analysis and consultations with a statistician, a decision was taken to restrict sampling to just two estimates of MFA per ring. It was concluded that two estimates per ring would be enough to give reliable estimates of the changing microfibril angle trends between rings, trees and provenances of the Sitka spruce trees. This is in agreement with Donaldson and Frankland (1997) who suggested that 2-3 measurements per sample were enough as long as it was possible to visually select typical fibres for measurement.

5.6.3 Strength and stiffness sampling method

After the core (radial) section was removed from the 40 cm disc for microfibril angle analysis, two slabs remained. Three small clear specimens were taken at random from these two outside slabs (Figure 5.1F). The small clear specimens measured 2 cm x 2 cm x 30 cm. This yielded a total data set of ninety six (i.e. four provenances, eight trees, three samples within each tree) for each of the strength and stiffness tests.

5.6.4 Wood density sampling method

The samples for the density measurements came from discs taken from the bottom of the 50 cm sample disc taken from each tree (Figure 5.1G). The discs removed were approximately 5 cm high. A core (radial) section from northeast to southwest was taken from this 5 cm disc. This core section was then cut to 5 mm in height and 15 mm in width (Figure 5.1H). The density was measured from the northeast side of the tree only.

5.6.5 Establishing the relationship between MFA and MOE / MOR

In order to establish the relationship between MFA and MOE/MOR, estimates of MFA and MOE/MOR were taken from the same wood sample. To facilitate this, one of the three small clear specimens taken per tree as described in section 5.6.3 was chosen at random. In order to allow MFA measurements to be taken, a piece approximately 25 mm long was cut from one end of each of the small clear specimens. The middle ring of this piece was marked and the sample was split along that ring. Both sides of the sample were clearly labelled. A matchstick sized sample was then taken from the earlywood of this sample ring. The rings that composed the small clear specimens were not known.

5.7 METHODS OF MEASURING WOOD PROPERTIES

5.7.1 Microfibril angle measurements

The main objective of this study was to establish whether the average microfibril angle varied according to provenance. To do this the MFA from a selection of rings was measured for each of the thirty-two trees.

5.7.1.1 Measuring microfibril angle

Initially it was intended to measure microfibril angle using x-ray diffraction. However, no suitable x-ray diffraction machine could be located in Ireland. Therefore, it was decided to measure the angles using polarised light microscopy. The method of microfibril angle measurement was that of Donaldson (1991).

5.7.1.2 Preparing samples for polarising light microscopy

Each small matchstick sample for microfibril angle measurement (section 5.6.1) was placed in a 50/50 mixture of acetic acid and hydrogen peroxide and heated at 60° C for 24 hours. This procedure caused the samples to become delignified which facilitated the separation of the individual fibres. The fibres were then rinsed in distilled water to remove the maceration solution. The rinsed fibres were placed directly onto microscope slides, at a 90° angle to the short axis of the slide. This was done as accurately as possible by hand. The microfibril angle was viewed through the bordered pits on the cell walls of the fibres. This ensured that the microfibril angle of just one cell wall was being measured. The slides were placed on to a rotating plate and viewed under the microscope. The angle from the 90° position to the maximum extinction position was recorded. This angle could be read easily from the rotating plate. This measured angle relates directly to the microfibril angle of the S2 cell wall layer.

5.7.2 Measurement of Modulus of Elasticity and Modulus of Rupture

Stiffness i.e. modulus of elasticity, and strength i.e. modulus of rupture, were measured using small clear specimen testing. The small clear specimens were tested using the central loading method (B.S. 373, 1957). Prior to testing the small clear specimens were stored under controlled temperature and humidity conditions (20 °C ± 3 °C and 65% ± 2% relative humidity).

Modulus of Elasticity (MOE): The modulus of elasticity is an index of the stiffness of a piece of wood. In this study it was measured using the central loading method. Using this method the ends of the sample were supported and a load placed on the centre of the sample. The test pieces were supported at the ends in such a way that they were quite free to follow the bending action and were not restrained by friction which would resist the bending and tend to introduce longitudinal stresses. In accordance with BS 373 (1957) the loading heads moved at a constant speed of 0.65 cm min^{-1}. The orientation of the annual rings in the 2 cm standard test piece was parallel to the direction of loading. The deflection of the beam at mid-length was measured with reference to the outer points of loading in the central loading method.

The formula used for the calculation of MOE was:

$$\frac{P' / L^3}{4\Delta' / bh^3}$$

where: P' = Load at limit of proportionality (N)

L = Length of test piece (mm)

Δ' = Deflection at mid length at limit of proportionality (mm)

b = Breadth of test piece (mm)

h = Depth of test piece (mm)

(B.S. 373, 1957).

Modulus of Rupture (MOR): The modulus of rupture is the maximum load a wood sample can sustain prior to rupture. The MOR was determined using a similar test procedure as outlined for MOE. However, for the MOR test, the maximum load prior to rupture was recorded and this was used to calculate the MOR as follows:

$$\frac{3PL}{2bh^3}$$

where: P = Maximum load (N)
L = Length of test piece (mm)
b = Breadth of test piece (mm)
h = Depth of test piece (mm)
(B.S. 373, 1957).

5.7.3 Density measurements

The method of wood density determination followed was that of Evertsen (1988). An x-ray image was taken of each of the thirty-two 5 mm samples (section 5.6.4), on to x-ray film. Each x-ray film was made up of 2-3 samples, a calibration stepwedge image and a linear slope for linear calibration of the x-ray film. A microdensitometer was used to read the density of the x-ray films. X-ray densitometry measures the amount of light that gets through the sample images and the x-ray film.

5.7.3.1 X-ray densitometry

The densitometer used was a Joyce-Loebl 3D machine with a PC based data acquisition system. Before scanning, the film was calibrated for film focus and linearity. Scan length and speed were determined. Linearity must be found before any of the sample x-rays can be scanned. The stepwedge was then scanned along the best fit linearity. From the data taken from the calibration, the correlation, slope and intercept of the film (line) could be calculated. This equation was used to compute the optical wood density equivalent of the optical readings. Each of the x-ray samples could then also be scanned along the best-fit linearity. Optical density readings were taken every 20 μm along the length of the sample. The optical readings taken from each of these samples could then be used to give the optical wood density equivalent readings, by using the slope and intercept values from the stepwedge as follows:

$$Y=mx+c$$

where: Y = Optical wood density equivalent reading
m = Optical density reading
x = slope
c = intercept

Once the optical equivalent density readings were calculated the data from each sample were plotted. These readings were then averaged to yield an average optical density value per tree. The optical density data collected were also weighted by the cross sectional area of the stem that the samples represented, thus, giving a new set of weighted density data.

5.7.4 Combined MFA and MOE / MOR measurements

The MOE and MOR measurements were taken in a manner similar to that outlined in section 5.7.2. For the MFA measurements slides were prepared as previously described in section 5.7.1.2. Three measurements of MFA were made for each ring sampled. These measurements were then averaged to give one MFA value per small clear specimen.

5.8 STATISTICAL ANALYSIS

The experimental design for the MFA, MOE, MOR and density data was deemed to be a 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 subjected to analysis of variance tests to determine how these characteristics differed according to provenance. The data were originally entered into Microsoft Excel and then analysed in GENSTAT ™.

6 Results

6.1 MICROFIBRIL ANGLE

Eight trees were taken from each of four Sitka spruce provenances. Within each of these trees, four annual rings (2, 5, 10 and 14 from the pith) were sampled and two MFA measurements taken per ring.

An examination of the MFAs in the various rings showed that for rings 2 and 14 there was little difference in the mean values for each provenance (Table 6.1). In rings 5 and 10 differences in the mean MFA values for each provenance were quite large. Considerable differences in mean MFA values occurred between rings with MFA declining from the pith (ring 2) outwards.

Table 6.1 - Mean MFA per ring per provenance

Provenance	Ring 2	Ring 5	Ring 10	Ring 14
California	22.00	24.75	20.62	11.75
Oregon	20.12	18.25	18.19	10.63
Q.C.I.	20.94	18.69	16.75	11.38
Washington	20.75	17.44	16.19	9.38
Standard error	0.68			

The analysis of variance of the MFA data (Table 6.2) showed that:

(1) MFA differed significantly between provenances (F ratio of 43.56, Prob.(F) < 0.001)

(2) MFA differed significantly between rings (F ratio of 360.03, Prob.(F) < 0.001)

(3) There was a significant interaction between ring and provenance with respect to MFA (F ratio of 8.21, Prob.(F) < 0.001).

Table 6.2 - Analysis of variance (ANOVA) of microfibril angle data

Source of variation	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob. (F)
Main plot					
Provenance	3	536.418	178.806	43.56	<0.001
Main plot error	28	114.922	4.104	1.11	
Sub-plot					
Ring	3	3,992.730	1,330.910	360.03	<0.001
Provenance*ring	9	273.129	30.348	8.21	<0.001
Sub-plot error	84	310.516	3.697	0.82	
Residual	128	575.500	4.496		
Total	255	5,803.215			

The interaction between ring and provenance is evident from the mean microfibril angle recorded per ring in the four provenances (Table 6.1). While for three of the provenances the MFAs were highest near the pith, declining gradually towards the bark, the value for MFA peaked in ring 5 for the Californian

provenance. A statistical comparison of the means in table 6.2 showed that for all provenances, with the exception of the Californian provenance, the mean MFA in ring 2 was significantly greater than the MFAs in the other rings. Similarly, for all of the provenances the MFA in ring 14 was significantly lower than the MFAs in the other rings. In contrast to the other provenances, the mean MFA of the Californian provenance was highest at ring 5. This MFA was significantly greater than the MFAs at ring 5 for the other provenances. Similarly, the MFA at ring 10 for the Californian provenance was significantly greater than the MFA for this ring for the other provenances.

6.2 ANALYSIS OF MOE DATA

A total of ninety-six MOE values were recorded, twenty-four from each provenance. The Washington provenance had the highest mean MOE value (Table 6.3), while the Californian provenance had the lowest.

Table 6.3 - Mean MOE per provenance with associated standard error

Provenance	Mean MOE (N mm^{-2})
California	7,377
Oregon	8,775
Q.C.I.	8,587
Washington	8,836
Standard error	909

The MOE data were subjected to an analysis of variance (Table 6.4) which showed that there was no statistically significant differences between provenances (F ratio of 1.14, Prob.(F)=0.35).

Table 6.4 - ANOVA table, showing the impact of provenance on MOE

Source of variation	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob.(F)
Provenance	3	3.389E+07	1.130E+07	1.14	0.35
Residual	28	2.777E+08	9.919E+06	14.84	
Subsample variation	63(1)	4.210E+07	6.683E+05		
Total	94(1)	3.537E+08			

6.3 ANALYSIS OF MOR DATA

Ninety-six MOR values were also recorded. The Washington provenance had the highest mean MOR value, while the Californian provenance had the lowest value (Table 6.5).

Table 6.5 - Mean MOR per provenance with associated standard error

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

An analysis of variance of the MOR data (Table 6.6) confirmed that the differences in the mean MOR values for each provenance were not significant (F ratio of 1.82, Prob.(F)=0.17). However, results from a pair-wise comparison of the four provenance means showed that the mean MOR of the Californian provenance differed significantly from the mean MOR of the Washington provenance.

Table 6.6 - ANOVA table showing the impact of provenance on MOR

Source of variation	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob.(F)
Provenance	3	1,595.88	531.96	1.82	0.17
Residual	28	8,170.35	291.80	6.91	
Subsample variation	63(1)	2,659.88	42.22		
Total	94(1)	12,421.11			

6.4 RELATIONSHIP BETWEEN MFA AND MOE

One of the objectives 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 this end, one wood sample was taken per tree and the mean MFA and MOE for that sample recorded. A sample was taken from each of the eight trees per provenance, yielding a total data set of thirty-two readings.

The MFA and MOE data for the provenances were plotted (Figure 6.1). While there appears to be an overall linear trend in the MFA and MOE data, there is no suggestion from this plot that four separate lines with different slopes and intercepts would be needed to describe the relationship between MFA and MOE for the four provenances.

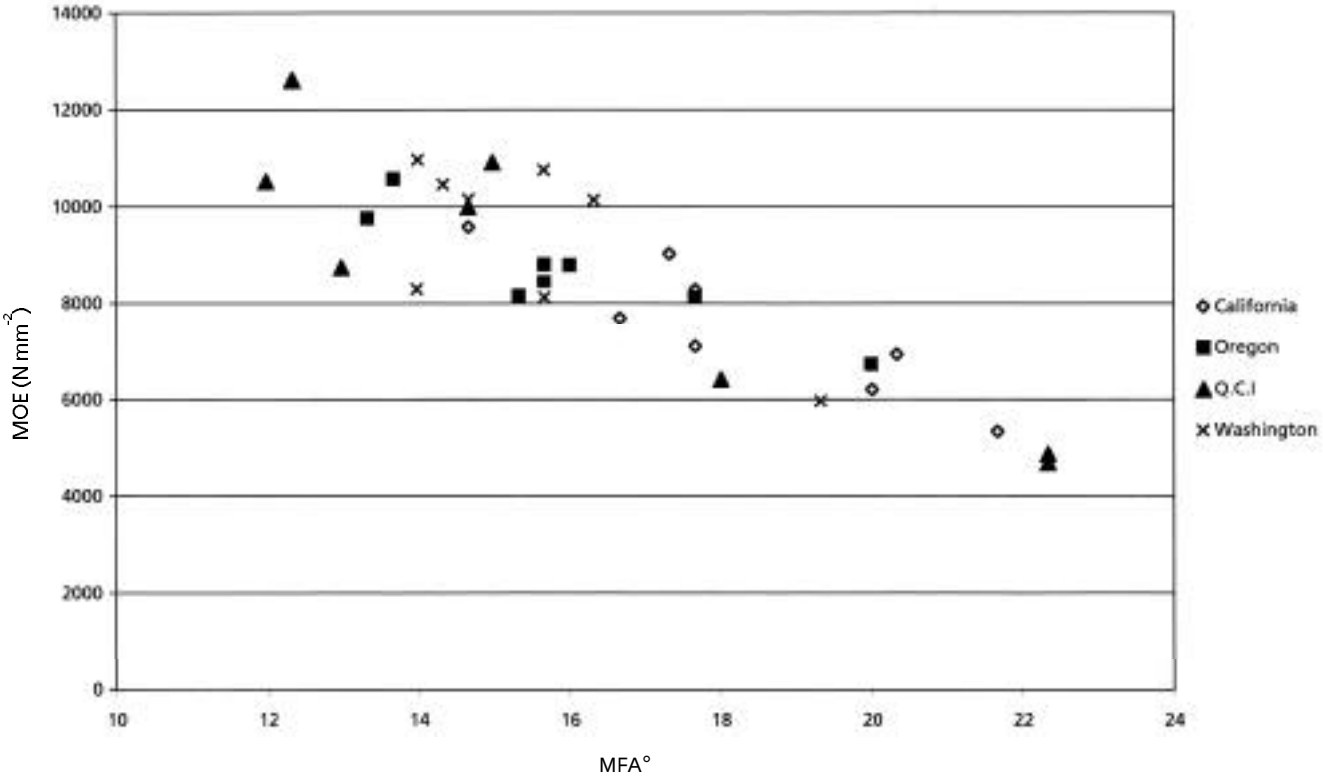


Figure 6.1: The relationship between MFA and MOE for each of the four provenances

Regression analysis was conducted to determine whether the relationship between MFA and MOE was the same for the four provenances i.e. would one equation be sufficient to describe the relationship or would four separate equations be required. Three regression models were run:

(1) MOE = MFA + Provenance + MFA*Provenance

(2) MOE = MFA + Provenance

(3) MOE = MFA

A statistical comparison of models 1 and 2 showed that the interaction between provenance and MFA was not significant. In other words, equations with different intercepts and slopes were not required for the four provenances. A statistical comparison of models 2 and 3 (Table 6.7) showed that the provenance effect was not significant. In effect this confirmed that one equation was sufficient to describe the relationship between MFA and MOE for the four provenances of Sitka spruce examined. This equation is as follows;

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

Table 6.7 - Regression analysis showing the MFA effect only on MOE (Model 3)

Model	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob.(F)
Regression (MFA)	1	9.212E+07	92,119,775	101.57	<0.001
Residual	30	2.721E+07	906,940		
Total	31	1.193E+08	3,849,289		

R-square = 76.4%

The regression analysis (Table 6.7) shows that over 76% of the variation in MOE data can be attributed to MFA. Figure 6.2 shows the relationship between the MFA and the MOE data graphed with the best fitting line.

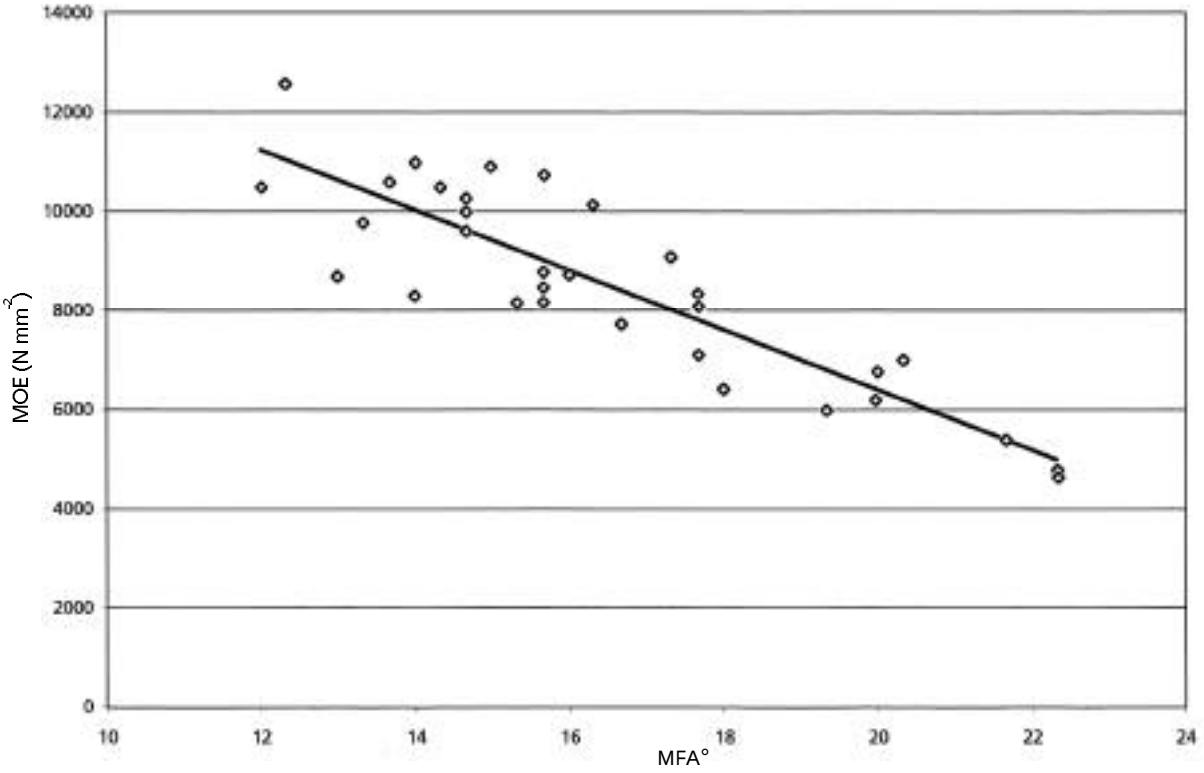


Figure 6.2: The relationship between microfibril angle and modulus of elasticity

The series of regression analyses were re-run but with provenance represented by the respective latitudes and treated as a continuous variable in the analysis. The results were similar to those described above.

6.5 RELATIONSHIP BETWEEN MFA AND MOR

Measurements of MFA and MOR were also collected from the same wood sample. One sample was taken from each of the eight trees from the four provenances, giving a total data set of thirty-two observations.

The MFA and MOR data for the provenances were plotted (Figure 6.3). While there appears to be a linear trend in the MFA and MOR data, there is no suggestion from this plot that four separate lines with different slopes and intercepts would be needed to describe the relationship between MFA and MOR for the four provenances. In addition, there appears to be greater variation in MOR values than was noted for the MOE data, for given MFA values.

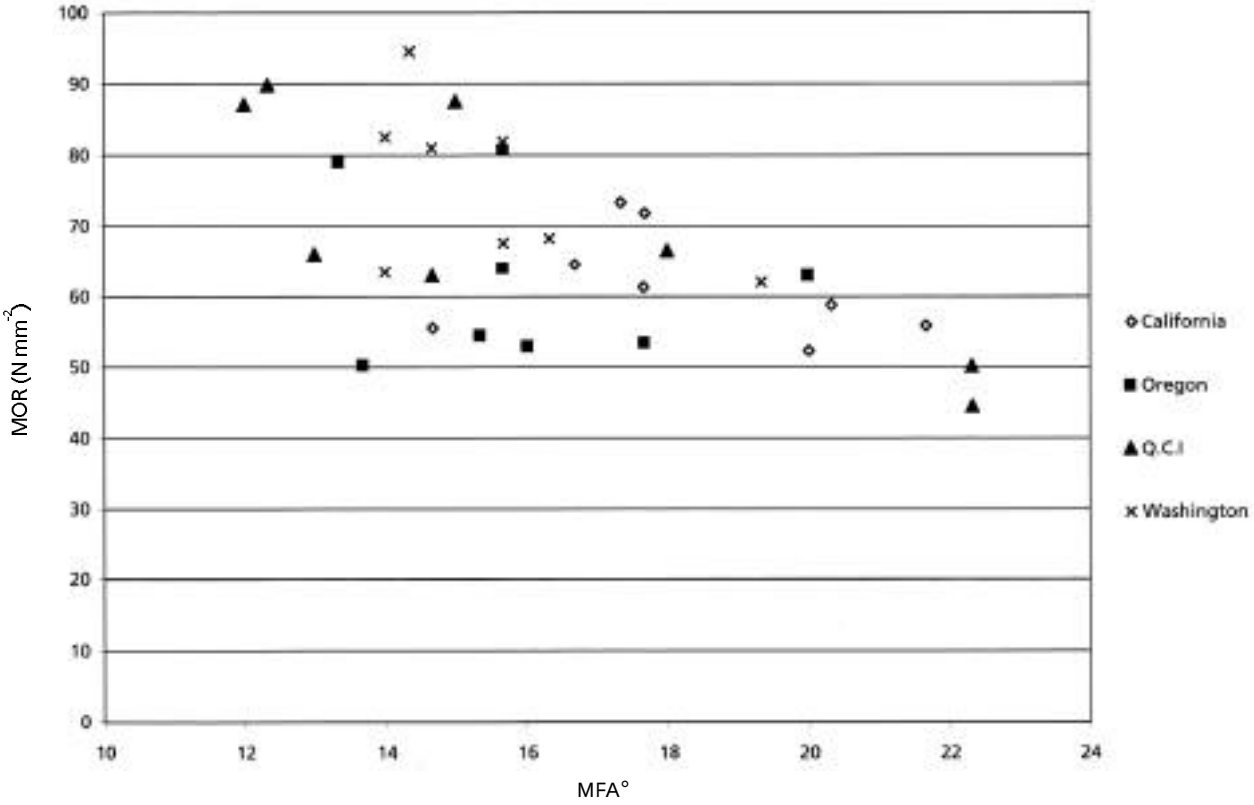


Figure 6.3: The relationship between MFA and MOR for each of the four provenances

Regression analysis was conducted on these data to determine whether the relationship between MFA and MOR was the same for the four provenances. The three regression models run were:

(1) MOR = MFA + Provenance + MFA*Provenance
(2) MOR = MFA + Provenance
(3) MOR = MFA

A statistical comparison of models 1 and 2 showed that the interaction between provenance and MFA was not statistically significant . This showed that equations with different intercepts and slopes were not

required for the four provenances. A comparison of models 2 and 3 (Table 6.8) showed that the provenance effect was not significant. In effect this confirmed that one equation was sufficient to describe the relationship between MFA and MOR for the four provenances. This equation is as follows:

$$MOR = 113.2\text{-}2.8(MFA°)$$

Table 6.8 - Regression analysis showing the MFA effect only on MOR

Model	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob.(F)
Regression (MFA)	1	1,963	1,963.2	17.08	<0.005
Residual	30	3,449	115.0		
Total	31	5,412	174.6		

R-Square = 34.1%

In contrast to the regression analysis of MFA and MOE, where 76% of variation in MOE was explained by MFA, the MFA only accounts for 34% of the variation in MOR. Figure 6.4 shows the relationship between the MFA and the MOR data graphed with the best fitting line.

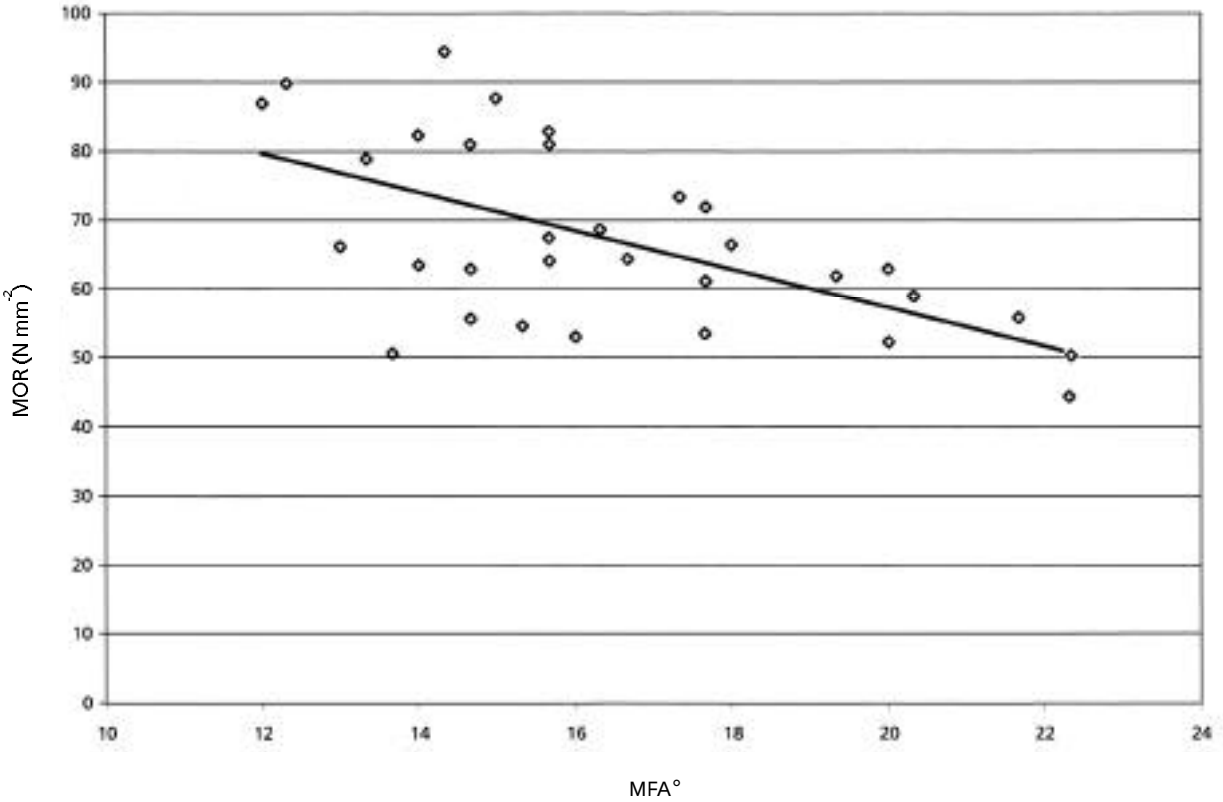


Figure 6.4 : The relationship between microfibril angle and modulus of rupture

The series of regression analyses were re-run but with the provenances represented by their respective latitudes and treated as a continuous variable in the analysis. The results of the analysis were similar to those found above.

6.6 OPTICAL DENSITY DATA

Optical density readings were taken from each of the eight trees selected from the four provenances. The optical density readings were taken from the first fourteen rings of the trees sampled and then averaged to give an average optical density reading for each tree. The Q.C.I. provenance had the highest mean optical density, while the Oregon provenance had the lowest mean optical density (Table 6.9).

Table 6.9 - Mean optical density per provenance with associated standard error

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

An analysis of variance (Table 6.10) carried out on the density data confirmed that the differences between the mean optical density values of the provenances were not significant at the 5% level (F ratio of 2.53, Prob.(F)=0.08), but were significant at the 10% level.

Table 6.10 - ANOVA table, showing the impact of provenance on density

Source of variation	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob.(F)
Provenance	3	17,641	5,880	2.53	0.08
Residual	28	65,074	2,324		
Total	31	82,714			

A pair-wise comparison of the means in table 6.9 confirmed that the difference between the optical density value in the Oregon provenance and the Q.C.I. provenance was significant. No significant differences were noted between any of the other provenances.

6.7 WEIGHTED DENSITY DATA

As outlined in Section 5.7.3.1 the optical density readings were weighted by the cross section of the stem from which the samples were drawn (Table 6.11).

Table 6.11 - Mean weighted density per provenance with the associated standard error

Provenance	Mean weighted density (kg m^{-3})
California	504.4
Oregon	485.6
Q.C.I.	553.6
Washington	529.2
Standard error	26.88

The analysis of these weighted values showed that there were no significant differences in the weighted density values per provenance (Table 6.12) at the 5% level, but the difference was significant at the 10% level.

Table 6.12 - ANOVA, showing the impact of provenance on weighted density

Source of variation	Degrees of freedom	Sum of squares	Mean square	F ratio	Prob.(F)
Provenance	3	21,028	7,009	2.43	0.087
Residual	28	80,906	2,889		
Total	31	101,934			

A pair-wise comparison of the weighted density means confirmed that the mean weighted value for the Oregon provenance differed significantly from that for the Q.C.I. provenance. No significant differences were noted between any of the other provenance means.

7 Discussion, conclusions and recommendations

7.1 INTRODUCTION

The objective of this work was to describe the microstructure of Sitka spruce wood. In particular, it aimed to determine the relationship between the wood microstructure of four Sitka spruce provenances grown in Ireland and the quality of the timber produced from them. Density, microfibril angle, strength and stiffness were the attributes measured.

7.2 DENSITY

Wood density has been the focus of much research in the past and has traditionally been the factor on which most wood quality improvement programmes were based (Walker and Butterfield, 1996; Murphy and Pfeifer, 1990). One of the reasons for this is that density is a very good indicator of wood strength (Cown, 1992; Schniewind, 1989; Addis Tsehaye et al., 1995b; Walker and Butterfield, 1996). However, in recent years the emphasis on strength as an absolute indicator of wood quality has declined. Instead, stiffness is increasingly considered to be a better indicator as it is the characteristic that most often governs the design of timber structures. Yet, density has been shown to be a poor indicator of stiffness (Walker and Butterfield, 1996; Cave and Walker, 1994; Addis Tsehaye et al., 1995a). Trials carried out by Brazier (1986) indicated that wood density, though of some significance in wood strength, was not as important as some other factors which lowered performance of wood in use.

From a tree breeding perspective, density has some advantages in that it has been shown to be a highly heritable trait (Cown et al., 1992; Zobel and Jett, 1995). At the same time a trait whose value in mature wood is highly correlated with its value in juvenile material also presents advantages in a breeding programme, in that such programmes can be shortened. Research to date on density, especially in Monterey pine, would suggest that there is a weak relationship between density in juvenile wood and density in mature wood (Senft and Bendtsen, 1985; Cown, 1992; Walker and Butterfield, 1996). Therefore, selecting on the basis of density from young trees may not be a very reliable method of improving wood quality. However, density remains an important indicator of wood strength. Information on the density of Irish grown Sitka spruce provenances is limited. In order to redress this information gap, the density of the four Sitka spruce provenances was examined.

The results from this research showed that the trees from the Queen Charlotte Island provenance produced the timber with the highest density, while the trees from the Oregon provenance had the lowest density timber. The difference in optical density between the aforementioned provenances was statistically significant and amounted to a 10% difference. These results are similar to results found by Jeffers (1959) and Murphy and Pfeifer (1990) who both observed a trend toward lower wood density with more southerly provenances. The extent of the difference is in agreement with the trend found by Thompson (1995a).

It is important to recall that optical density values were compared and not actual density values. However, there is no reason to believe that relative differences in optical density values would differ from relative differences in actual density values. This study showed considerable variation in density within a provenance. For example, for the trees selected from the Queen Charlotte Island provenance the optical density values ranged from 479 kg m^{-3} to 682 kg m^{-3}. Thus, the difference in wood density between trees

within any provenance was large and was greater than the corresponding differences between provenances. This range in values occurred in spite of efforts made at the sampling stage to minimise variation by assuring that all of the samples came from the same position in the tree i.e. the north east cardinal point at a level straddling breast height. This variation between trees of the selected provenances might explain why only the density in the Q.C.I. and Oregon provenances were shown to differ significantly.

7.3 MICROFIBRIL ANGLE

Microfibril angle research had not been carried out previously in Ireland. There is also limited research world-wide into microfibril angle variations among provenances. Studies in Australia and New Zealand relate mainly to clones of Monterey pine. The results from these clonal trials have shown that a strong relationship exists between MFA and wood stiffness and also that MFA is under some degree of genetic control (Walker and Butterfield, 1996; Cave and Walker, 1994; Cowdrey and Preston, 1966). A similarly strong linear relationship between MFA and wood stiffness was found by Brazier (1986) for Sitka spruce.

Tree breeders are becoming more interested in microfibril angle, not only because of its correlation with stiffness (Walker and Butterfield, 1996; Cave and Walker, 1994; Cowdrey and Preston, 1966), but also because its value in juvenile wood is a good indicator of its value in mature wood. Several researchers have reported that the MFA always declines with age (Walker and Butterfield, 1996; Donaldson, 1993; Pedini, 1992). Walker and Butterfield (1996) reported that MFA either declines noticeably with distance from the pith or it declines only gradually. It has been suggested (Walker and Butterfield, 1996; Donaldson 1992; Donaldson 1996) that selection on the basis of MFA rather than density is a better method of selecting for improved wood quality.

The results of the microfibril angle measurements from the four Sitka spruce provenances examined in this study showed that differences in values between annual rings were significant. The general trend was for the microfibril angle to be greatest near the pith and then to decline gradually towards the cambium. Such trends have been found previously for both Norway and Sitka spruce (Saranpaa et al., 1997; Philips, 1941; Pedini, 1992). The research showed that for three of the four provenances examined, the MFA was at its greatest in ring 2, where angles as high as 22° were recorded. The lowest MFAs for all four provenances were found in ring 14 where the angle varied from just 9° to 11°.

However, differences between provenances for specific rings were limited. The general trend of decreasing MFA with distance from the pith differed for the Californian provenance. With the Californian provenance the highest MFA occurred in ring 5 rather than ring 2, before following the trend of decreasing MFA towards the cambium. This MFA at ring 5 was shown to be significantly greater than the MFAs at ring 5 for the other three provenances. This was also true for the MFA value at ring 10. No clear explanation could be discovered as to why this trend across rings is different for Californian Sitka spruce. The Californian provenance has the most rapid growth rate and this may be in some way linked. The high value in ring 5 may also be due to the presence of compression wood, which is a feature of rapidly growing trees. Differences between the other provenances for specific rings were not as prominent. However, the results clearly show that greater variation exists across rings than between provenances.

7.4 MFA AND STRENGTH AND STIFFNESS

The strong relationship between MOE and MFA which has previously been shown (Brazier, 1986) was confirmed in this study, when the regression analysis showed that a straight line fit the data very well. Thus, as the MFA increases the MOE decreases. There was clear evidence that a single regression line could be used to describe the relationship between MFA and MOE for the four provenances of Sitka spruce. The model showed that for a decrease in MFA of 22° to 12°, the MOE increased from 5,185 N mm^{-2} to 11,246 N mm^{-2}. Thus, for any provenance, the increase in stiffness between wood formed at the pith and wood formed at ring 14 may be as high as 115%.

The relationship between MFA and MOR is known to be weak (Addis Tsehaye et al., 1995a). This was confirmed in the study from a plot of the data and the regression analysis. The model suggests that a similar reduction in MFA as outlined above, causes MOR to increase by only 54%. Similarly, no evidence of any difference between provenances in the relationship between MOR and MFA was found.

No significant differences were found in the mean MOE values for the four provenances tested. In contrast, a significant difference was found between the mean MOR value of the pieces sampled from the Californian provenance and those taken from the Washington provenance. A possible explanation for this is that the Washington provenance has the lowest MFA value while the Californian provenance has the highest. While the relationship between MFA and MOR is not as strong as that between MFA and MOE, it is still a linear relationship which may account for the MOR trend.

7.5 CONCLUSIONS

The conclusions from this study can be summarised as follows:

(1) Little differences were detected between the mean MFA for the four provenances. The Californian provenance did exhibit significantly greater MFAs than the other three provenances in both ring 2 and ring 5.

(2) Substantial differences were detected in MFA from pith to cambium in all provenances. This indicates that variation in MFA is greater within trees than between provenances.

(3) A strong negative linear relationship was found to exist between MFA and MOE. A single regression line can be used to describe the relationship between MFA and MOE for the four provenances examined.

(4) No significant differences in wood stiffness were detected between wood samples taken from trees of different provenances. However, the wood from the trees of Washington origin was stronger than the wood produced by the trees of Californian origin.

(5) There was a statistically significant difference in optical wood density between the trees of Q.C.I. origin and the trees of Oregon origin.

(6) There was a statistically significant difference in MOR between the Washington and Californian provenances.

7.6 RECOMMENDATIONS

The commercial implications based on the above findings and conclusions may be summarised as follows:

(1) In a genetic improvement programme a reduction in the MFA may be targeted, especially in the early part of the juvenile wood.

(2) When considering provenance selection based on 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 the Q.C.I. provenance based on selection for density.

(3) When considering provenance selection based on MFA, the Californian provenance showed a significantly higher MFA in the juvenile wood. Based only on the data presented here, a further study may be required or this provenance may be best avoided.

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