DOCTOR OF PHILOSOPHY

The effects of seed origin and site on the amenability of Sitka spruce to preservative treatment

Usta, Ilker

Award date:
1997

Awarding institution:
University of Wales, Bangor

The Effects of Seed Origin and Site on the Amenability of Sitka spruce to Preservative Treatment

A Thesis submitted to the University of Wales
for the Degree of *Philosophae Doctor* in Wood Science

by
Ilker USTA

Forest and Fibre Research Group
School of Agricultural and Forest Sciences
University of Wales, Bangor, United Kingdom

November 1997

To my wife Ayse
who has always given me stimulus to carry out my post-graduate studies
and for bearing my absence.
To my son Mert
who has always welcomed me with a smile.
To my parents
who have ever given incentive and aid for me to follow my vocation.

Acknowledgements

I am most grateful to the following people and organisation, for the assistance they have offered me in one way or another which has enabled me to carry out this work:

- Turkish Higher Educational Council (YOK), Hacettepe University, and Department of Wood Processing Industrial Engineering (AEM), for the provision of a grant.

- Dr. M. D. C. Hale, for the overall guidance with his unreserved help, advice and encouragement he gave me to complete this study and for reviewing this thesis.

- Dr. C. Cahalan, Dr. P. Denne and Dr. M. Breese, for their interest in the work and making available their expertise during the research with valuable suggestions.

- Forestry Commission's Forest Research Agency (Dr. S. Samuel, Dr. J. Webber, Mr. C. Jones, Mr. R. Howe) for supplying material from experiments at Rhondda and Dalby.

- Dr. C. Whitaker, for the statistical advice.

- Mr. M. Mitchell and Ms. D. Aebischer, for the useful and the innumerable discussions.

- Mr. J. Evans, Mr. W. Morris-Jones, Mrs. H. Simpson and Mrs. V. Whitbread, for all the help they gave me in the laboratory and for assisting me promptly when in need.

- Mustafa Saatci, Murat Alp, Gani Koza, Ali Mutlu, Nihat Cetin, for their friendship and support. I always remember our time playing *football* or having some *Turkish tea.*

Abstract

The variation in density, longitudinal and radial permeability was investigated in eight seed origins of Sitka spruce (Alaska -AL, British Colombia -BC, Queen Charlotte Islands -QCI, North Washington -NW, South Washington -SW, North Oregon -NO, South Oregon -SO, California -CA) grown at two sites in the UK (Dalby, Eastern England and Rhondda, South Wales).

Five trees of each seed origin at each site were sampled at three heights (1.3, 2.3 and 3.3 m above ground level). For the investigation of permeability, cylindirical plug samples (30 x 15 mm diameter) were used because this overcome problems of block orientation and allowed large numbers of samples to be tested. Outer sapwood plug samples were prepared with their long axis either in the longitudinal or the radial direction.

The density of the samples decreased withincreasing height within the stem. This corresponded to a trend of increasing ring width. The trees of seed origins NW, SW and NO at both sites, and QCI and SO at Rhondda had the highest wood density partly due to their slow rates of incremental growth. The seed origin CA had the lowest density on account of its rapid incremental growth. Therefore, it is suggested that to optimise density QCI, NW, SW and NO should be selected for plantation use. The seed origins AL and BC should be avoided in the future plantations as they grew poorly at both sites.

The wood permeability of the different sites showed an inverse relationship between longitudinal and radial permeability. The general trend showed that although they were less treated longitudinally, the trees on the Rhondda site were more treated radially as compared to those at Dalby. Results obtained in this study generally show that of the seed origins QCI and NW had the greatest permeability both longitudinally and radially. This is in contrast to NO and SO which had the lowest permeability longitudinally (NO) and radially (SO).

It appears that there are reasonable explanations for differences in longitudinal permeability and that the differences are linked to density which is in current breeding programs. Furthermore, the major influences on longitudinal permeability are associated with post-harvest processing, e.g. drying. Little is known however about radial permeability and differences seen in this study between QCI and SO (the most and least radially permeable) are investigated further in this thesis at an anatomical level.

The ray structure of these two seed origins was examined microscopically and different patterns of ray composition were observed. The most important anatomical features influencing radial permeability were the nature of both the ray tracheids and the ray parenchyma cells, and the condition of the cross-field pits in particular.

Contents

FIGURES		PAGE

TABLES		PAGE

1 INTRODUCTION

Foresters tend to concentrate on those species which are the easiest to handle silviculturally, and which will produce the greatest volume of generally useful wood in the shortest time. In temperate countries, forest managers have selected softwoods to supply the bulk of timber requirements with spectacular results in terms of wood volume production.

The fastest growing conifers tend to be pioneer species in the ecological sense, and this makes them amenable to treatment as a crop which can be planted or regenerated in pure stands. Although such monocultures carry inherent risks of soil deterioration and epidemics of pathogens, they are easier to manage and harvest. Thus, even aged stands are preferred for production forestry.

When planting is used to regenerate these stands, seedlings are planted in close proximity to each other so that in their early stages they grow in a thin upright form with little development of lateral branches. Successive thinning operations remove a high percentage of the slower growing and worst formed trees so that the full production potential of the site is concentrated on the trees which will form the final crop. These are usually harvested at the completion of the economic rotation (when the current annual increment of timber volume falls below the mean annual increment for the rotation). This is generally well before the trees have reached full biological maturity.

One result of this use of an economic rotation is that final crop trees contain a much lower proportion of heartwood than would be found in naturally occurring trees of the same species at full biological maturity. The trees felled in thinning operations consist of virtually all sapwood. While this is a desirable characteristic for the manufacture of pulp, if the wood is to be used in solid form it may be prone to biodeterioration.

Even where heartwood is present, the type produced by many of the fast growing conifers has very little natural durability. The heartwood of species such as larch (*Larix* spp.), Douglas-fir (*Pseudotsuga menziesii*) and some of the slower growing pines (*Pinus* spp.) will last for several years exposed to the elements provided it is not in contact with the ground. Only a few relatively slow growing conifers, e.g. Western red cedar (*Thuja plicata*), possess sufficient quantities of a suitable, insoluble, toxic material in the heartwood to allow it to be used under the demanding conditions of ground contact.

With the exception of a few animals which bore into wood for protection (e.g. Pholad marine borers, and some insects such as carpenter bees) most organisms which destroy wood do so in order to utilize the hemicellulose and cellulose as nutrients. Thus it is possible to protect wood from these organisms by poisoning the wood with preservatives or by chemically modifying it so that it is no longer suitable as a food source.

The main objective of the production forester is to maximise the return on the investment in the forest, (i.e. to yield timber with quality acceptable to the market), particularly for the more financially rewarding construction industry. There has however been concern that much of the plantation grown Sitka spruce in the United Kingdom is on the borderline of acceptability for structural performance (Brazier, 1977). The most important area of influence that the forester has in manipulating the quality of the timber is genetic control (e.g. the species, provenance and selected genotype), and the second area is the management of growing trees. Therefore, a programme of tree and timber selection is being undertaken (by the Forestry Commission) for Sitka spruce in order to recognize and in due course to breed from those trees combining high yield and good timber quality.

The timber of Sitka spruce is grown in the UK used for such purposes as construction work, cladding, packing, and pulp. However, much of this plantation growth is light in weight for these (constructional) purposes and it would be improved by an increase in density, if possible from an increase in earlywood density. This should result in a more uniform texture, which might be expected to give the timber better working and finishing properties as well as reduce collapse on drying. A reduction in the number of trees with marked spiral grain should also contribute to improved timber quality. Spiral grain logs gives cross-grained lumber on conversion. This distorts and twists on drying; it also requires more care in machining and has reduced strength properties in comparison with more nearly straight-grained wood of comparable density. An improvement in its quality as pulpwood might be expected from attention to cell size and associated cell wall structure, as well as from an increase in density to improve yield per volume. For all purposes, selection of trees reaching an adult condition for fibre length, density, grain angle, at an early age or small size would increase the yield of better-quality wood. It is therefore most important to recognise and understand both direct and indirect factors which control density and influence its variability within the tree.

In addition to its effects on mechanical properties, density has an influence on resistance to biological attack (Nilsson and Daniel, 1992) and higher density may reduce the void volume for preservative treatment. Despite this, increases in density within a species are generally associated with increases in latewood proportion. As latewood is a residual pathway of preservative flow in dried softwoods, density increases may increase permeability of softwoods. Thus, density is an important factor with preservative studies.

1.1 Scope of the Study

In British forestry, Sitka spruce is the most widely planted species. The success of Sitka spruce can be attributed to its ability to grow on a wide range of sites (often under poor conditions) and to have a good stem form (where the stems are generally straight and the branching habit of most trees is satisfactory) and a high proportion of vigourous growth (i.e. the yields of Sitka spruce generally exceed those of other species).

Sitka spruce sapwood is generally regarded as being very permeable to fluid before drying (Erickson, 1970) but after drying it is much less permeable (Phillips, 1933) and is classed as resistant to preservative treatment (Siau, 1984). It is generally believed that the cause of loss of permeability is axial tracheid bordered pit aspiration in the earlywood where the pit margo and torus are displaced when air bubbles move past the membrane as would typically occur during drying (Petty, 1970). In a situation such as pole treatment, longitudinal flow treats the pole ends very well, whereas the region of high risk, the ground line zone, is situated above this well-treated zone (Eaton and Hale, 1993). It is in this context that radial flow into the sapwood is particularly important.

Comstock (1970) has shown that in softwoods, longitudinal and tangential flow are controlled by the same factors but radial permeability is controlled independently. In many softwoods, tracheid pitting is concentrated on radial cell faces which favours flow in the tangential direction via a longitudinal route (i.e. along axial tracheids through tracheid pits, along axial tracheids through tracheid pits, etc.), and thus gives a long path length for tangential flow (Eaton and Hale, 1993). However, there is no real understanding in Comstock`s models how radial flow occurs.

The major problems in the treatment of spruce relate to the anatomical structure of the material. The bordered pit is normally considered the most important structure regulating the permeability of softwoods, but the rays have also been proven influential (Liese and Bauch, 1967). The small ray size and the cross-field pit structure may contribute to the radially refractory nature of spruce. Because of these factors, and the many failed attempts to effectively treat many of the different species of spruce, attempts to improve treatment may best be left to the use of physical modifications to the material, such as laser incising, improvements in drying method and treatment schedules and to the development and use of diffusible preservatives.

The principal aim of this thesis is to investigate the variation in radial permeability of Sitka spruce between eight seed origins extending from the north to the south of the natural range of Sitka spruce when grown at two sites, one in Eastern England and one in South Wales. Therefore, these seed origins were tested for their permeability characteristics. An explanation for the differences was then sought by a detailed examination of the structure of a small sample of the wood from selected seed origins.

Since density may have a direct influence on preservative uptake, and because density is a factor under genetic control, the study in this thesis also details the effect of seed origins on density. In addition to seed origins its variability both within and between trees and also between sites is examined. Other factors, including growth ring width and tree size are accounted for.

2 GENERAL LITERATURE REVIEW

2.1 Sitka Spruce: Its Importance in UK Forestry

Sitka spruce *(Picea sitchensis* (Bong.) Carr.) is the best adapted tree for growing in the wet upland parts of the United Kingdom (Mitchell, 1985; Savill, 1991). It is a species of the western seaboard of North America, from southern Alaska to northern California, but most of the trees planted in Britain are from seed of Queen Charlotte Island origin, which combines acceptable vigour and frost hardiness in British conditions (Harding, 1988).

The 1987 census shows that Sitka spruce represented 525,901 hectares which comprise some 23.6 per cent of the total area under coniferous forest. It was mostly planted in the north and west of Britain, in some areas comprising 90 per cent of all trees planted (Lines, 1987). Current planting consists of Sitka spruce and it is likely that it will continue to be planted on a large scale. There are now over 600,000 hectares of Sitka spruce in the UK, comprising approximately 27 per cent of the total forested area.

Sitka spruce is favoured because it is readily established, grows on a wide variety of sites, is tolerant of severe levels of exposure, is generally disease resistant, has a good stem form and gives a higher yield than most other species particularly on less fertile sites (Worrell, 1987; Harding, 1988).

Sitka spruce has a wide latitudinal distribution and large differences in growth rate are found between different seed origins. Material from the Queen Charlotte Islands (QCI) is the best adapted for use in Britain but increases in growth rate can be obtained by using more southern origins on sites which are not prone to early autumn frosts. For instance, Washington seed origins have been favoured in Denmark, and have proved successful in parts of southern Britain, and these may well perform better than the more northerly QCI origin if and when the climate of upland Britain becomes warmer (Fletcher, 1992).

2.2 The Wood Properties of Sitka Spruce

Sitka spruce is the only British softwood of commercial importance which produces an almost uniformly pale-coloured wood described as whitewood. The timber is similar to whitewood from southern Scandinavia (Norway spruce, *Picea abies*) and parts of northern and central Europe.

Most British plantation Sitka spruce is fairly fast grown and British timber is generally regarded as being only marginally acceptable for construction grade timber. The timber is light in weight, coarse in texture, has a relatively low density, and numerous large knots. Average density at 12 % moisture content is the region of 390 kgm^{-3} but wood density of this species varies considerably with distance from the pith, with height in the tree, between trees and with silvicultural management and site class; these density variations have been shown to influence critical strength properties, including breaking strength, elasticity and shrinkage. All the strength properties of Sitka spruce have been well characterised and provide a sound basis for its structural uses.

The light coloured timber is of lustrous appearance and sometimes has a very pale pink or pinkish brown colour in the central core. When dry, there is no real distinction between heartwood and sapwood. The timber dries rapidly but care is needed in drying if distortion (twist and cup) and degrade (splitting and loosening of knots) are to be minimised. There is, however, a wide variation in the extent of degrade on drying and also in the incidence of collapse. Kiln schedule-J (Pratt, 1986) proves satisfactory in most instances.

Sitka spruce is non-durable[1] and both the sapwood and heartwood are difficult to treat with preservative solutions by pressure impregnation, or in other words are resistant[2] (EN 350, 1994 part 2).

---

[1] Average life of 50 x 50 mm stakes in ground contact is 5 - 10 years

[2] These timbers are difficult to impregnate under pressure and require a long period of treatment. It is often very difficult to obtain more than about 3-6 mm lateral penetration. Incising is often used to obtain a better treatment.

2.3 Sitka Spruce Breeding in the UK

An intensive breeding programme has been carried out in Sitka spruce for more than 30 years with the aim of improving vigour, form and timber quality of the tree crop (Faulkner, 1987). Until recently, the main objectives of breeding were to increase volume growth rates and timber yields. Wood density is now also considered in the breeding programme.

Tree improvement is a combination of silviculture and tree breeding aimed at producing higher quality products. The tree breeding contribution consists of producing superior genotypes but these cannot fulfil their optimal potential unless appropriate silvicultural treatments are implemented. Genetic improvement of a species by breeding depends on the amount of genetic variability which is exhibited across its natural range and at the individual tree level.

There are three levels of genetic variability which the tree breeder can utilise, namely: species, provenance[1] (seed origin) and individual tree. In any tree breeding programme these three levels are to be exploited in that order (Fletcher, 1992).

2.3.1 Species Testing

The use that is made of exotic species depends to a large extent on the potential of indigenous species, and in Britain the native species do not have the potential to achieve the relatively fast rates of growth that are theoretically possible in the prevailing climatic conditions. It was this possibility for increasing production that was one of the main spurs for introducing new species to Britain where Sitka spruce mainly indicated its potential for rapid rates of growth, high volume production and ease of establishment.

[1] According to European Economic Community definitions, provenance is the place in which any stand of trees (whether native or not) is growing, and origin is the place in which a stand of native trees is growing, or the place from which a non-native stand was originally introduced. In general forestry use, the term provenance is commonly extended to mean not only the geographical source of the seed, but also the trees raised from it. This is the meaning which accords with definition in the standard work on forest terminology (Ford-Robertson, 1971).

2.3.2 Provenance (Seed Origin) Testing

Sitka spruce has a range along the Pacific coast of North America covering some 22 degrees of latitude but it is restricted throughout most of its range to a coastal strip only a few kilometres wide. It has a requirement for adequate supplies of moisture and high humidity during the growing season which explains its natural range (Harris, 1980).

As is illustrated in Figure 3.1, the natural range of Sitka spruce extends in a narrow coastal strip from Kodiak Island, Alaska to Mendocino Country, California. Its northern and southern limits are respectively 61 and 39 °N which covers a distance of nearly 3000 km. The strip is widest (as much as 210 km) in South Alaska and northern British Columbia, while in South Oregon and California it is strictly confined to the coastal fog belt. The species is unique amongst spruces in its restriction to humid oceanic conditions. It has been found at elevations above 900 m in South Alaska and British Colombia, but over most of its range it occurs below 300 m (Lines, 1987). The largest Sitka spruces occur on the Queen Charlotte Islands and in the rain forests of the Olympic Peninsula of Washington where the trees grow 80 m tall (Ruth, 1958; Savill, 1992).

The seed origin testing phase has indicated that there are differences between seed origins in growth rates, phenology and wood properties and that by selecting the correct seed origin gains can be achieved. The Queen Charlotte Islands origins are good general purpose sources which are reasonably frost hardy, resistant to exposure and produce acceptable timber. On less exposed, more favourable sites, especially in south-west England, Wales and parts of west Scotland, origins from Washington and on some sites Oregon can be used with increases in timber production but with the possibility of a slight decrease in strength properties. All the seed origin experiments have shown that there is large within origin variation in the characteristics measured, indicating that the potential for further improvement through breeding could be explored.

It was not until the IUFRO seed collections in 1969/70 that a truly comprehensive collection of material from throughout the whole distribution of the species became available (Fletcher, 1976). In 1969/70, there were 47 experiments consisting 185 seedlots.

These covered the natural range and the range of sites on which this species is used in Britain. A total of 70 seed origins were planted on 15 forest sites (not all origins are on all sites).

The results indicated that the southern origins (Oregon and California) were rather unstable but outstanding on the better sites and correspondingly poorer on the worst sites. The material from the Queen Charlotte Islands, Vancouver Island and Washington was more stable and would do well on a range of sites, while the northern material would not do well on good sites. The northern Oregon material was the fastest growing on all sites except those with early frost.

The majority of wood property studies have been based on material from Queen Charlotte Islands seed origins. Samples were tested from four seed origins in the Radnor experiment for wood density measurements but the results were affected by the variable stocking in the plots. The Queen Charlotte Islands origin had the highest density and Oregon the lowest. A wider range of origins from the 1960/61 series of experiments were sampled at nine years of age and again the northern origins had the highest wood density, due partly to their slower rates of growth. There was an inverse correlation between wood density and stem volume (Broughton, 1962; Brazier, 1972), a relationship which has also been found more recently in Ireland (Murphy and Pfeifer, 1990).

A study to determine whether there were differences in the strength properties of wood between a Queen Charlotte Islands and six Washington origins from a 1950 Gwydr (Wales) Forest planting showed no significant differences between the origins (Fletcher, 1976). Measurements of specific gravity, percentage latewood and tracheid length also showed no significant differences between the origins, although there was large within origin variation in these characters. It is possible therefore to select for individuals with high volume production but without a corresponding decrease in density. Considerable gains in growth rate (volume) can be achieved at the expense of a slight decrease in wood density.

Lines (1980) mentioned that a major International Union of Forest Research Organisations (IUFRO) series of experiments was planted in 1974/75 with up to 70 seed origins on 18 sites (ten in Scotland, four in England and four in Wales). Sixty four of these origins were used to study growth patterns and phenology in a nursery trial (Kraus and Lines, 1976). Date of growth cessation was shown to be highly correlated with latitude of seed origin. No overall pattern of flushing could be determined, though individual trees within origins varied strongly. The conclusion from the forest experiments after 10 years is broadly that height growth is inversely correlated with latitude (Lines and Samuel, 1987). However there is a very strong site x seed origin interaction, with the most southerly origins growing poorly on northern and environmentally severe sites, while the northern origins grew relatively better on northern sites.

After ten years of the forest experiments, it was concluded that those originating from the Queen Charlotte Islands (IUFRO No: 7111) were found to grow much faster than would be expected from their latitude of origin, while those from the mainland of British Colombia (7116) were much less vigorous than would be expected from a simple cline with latitude. On frosty sites the most southerly origins were frequently damaged and had serious losses. Sitka spruce from the middle Skeena River region (7112) grew very slowly, and more favourable sites North Oregon seedlots from the (7951) seed region grew best, while those from (7971) and (7972) in West Washington and some Vancouver Island (7116) origins grew faster than those from Queen Charlotte Islands (7111). These southern sources also grew well on sites close to the sea as far as 57 °N in Scotland. Use of these very fast-growing origins carries a possible risk that the timber density of some trees may be unacceptably low. Delobrate (1984) showed that in Sitka spruce seed origin trials in France, wood density decreased as growth-rate increased. Finally, it was mentioned that Alaskan origins (7986) and those from the introgression area in the upper Skeena River grew poorly in Britain, so it was suggested that they should be avoided in the future plantations.

2.3.3 Individual Tree Testing

The seed origin testing phase has identified the most suitable origins for British conditions but there is scope for further improvement by selecting good quality stands and superior individuals within these origins. The partitioning of the genetic variation between and within origins tends to vary by species and individual trait but on average for vigour characteristics 40 % is accounted for by variation between origins and 60 % by variation within origins.

There are very good correlations between measurements made at age 6 to 8 and 20 to 30 years of age (Gill, 1987; Lee, 1990) so preliminary selections of families for inclusion in the breeding population can be made at between 6 and 8 years of age. Parents which produce families that on average are 15 % greater in height than the Queen Charlotte Islands control and 7 % taller than the overall mean are included in the breeding population.

2.4 Anatomical Structure of Softwoods

Wood is a complex biological material, known also as secondary xylem. It is derived from the vascular cambium and develops in the stems and roots of most gymnosperms (Philipson *et al.*, 1971). It consists largely of an assemblage of thickened cell walls deposited by the cell cytoplasm during differentiation.

To understand the behaviour of wood, it is important to examine wood at several levels: macroscopic, microscopic, ultrastructural, and also at the molecular level.

2.4.1 Macroscopic Structure

Timber as a material can be defined as a low-density, cellular, polymeric composite (Dinwoodie, 1975), and is composed of elongated cells (tracheids in softwoods) most of which are oriented in the longitudinal direction of the stem. Adjacent cells are connected with each other through openings (pits) in the cell walls (Sjöström, 1993). These cells, varying in their shape according to their functions, provide the necessary mechanical strength to the tree and also perform the function of liquid transport. Shorter cells (parenchyma cells) function in the storage of reserve food supplies and represent living tissue in sapwood. In broad terms, 90 - 95 % of the cells are aligned in the vertical direction, while the remainder are present in bands (rays) aligned in the radial plane.

When a wedge-shaped segment of a trunk is seen with the naked eye, some macroscopic features are apparent (Figure 2.1). A cut perpendicular to the longitudinal axis of the stem is called a cross (transverse) section, a cut in the radial longitudinal plane is termed a radial section, and a longitudinal cut near the bark of the stem is described as a tangential section (Bodig and Jayne, 1982). On these sections the growth rings and wood rays are visible. The macro features of the surfaces appear quite different from each other according to the plane of sectioning (Haygreen and Bowyer, 1982; Tsoumis, 1991).

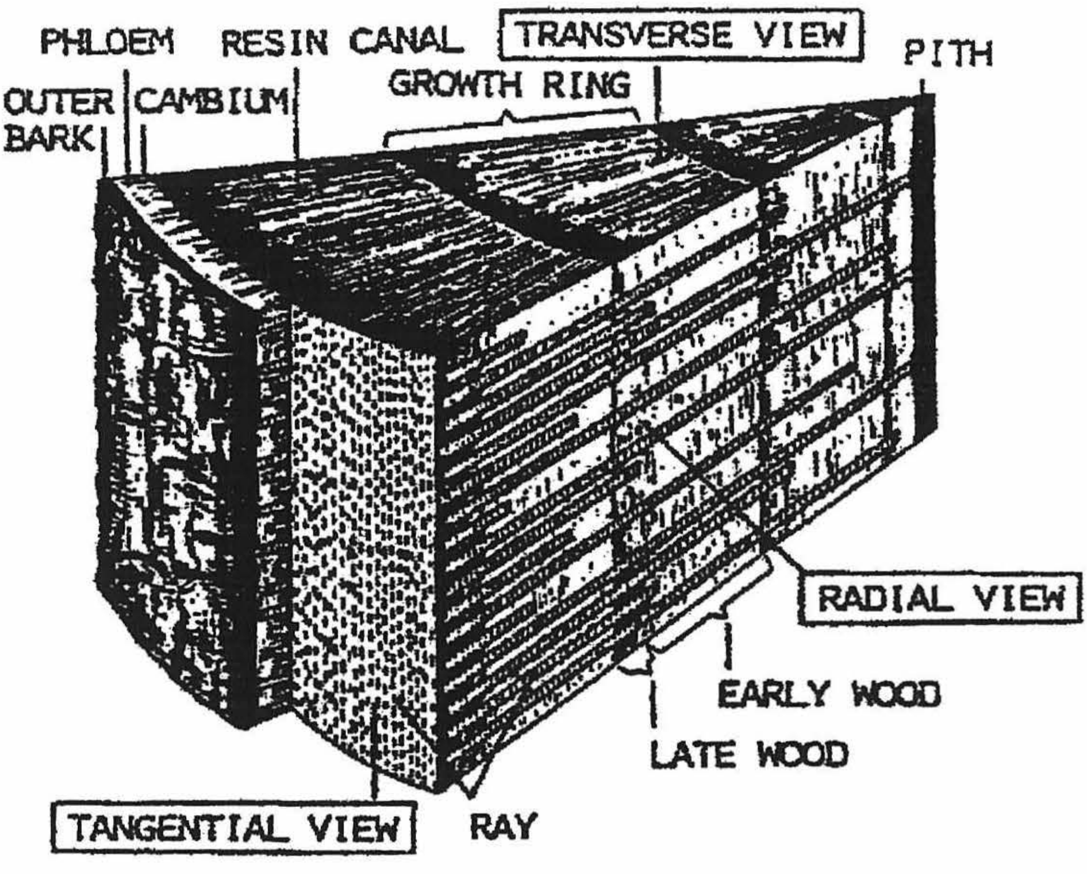


Figure 2.1. Sections of a typical softwood stem showing the macroscopic features of the timber (from Sjöström, 1993).

Characteristics of Transverse Surface (cross-section)

In most species, growth rings can be easily distinguished from one another because of differences between earlywood and latewood. The reason for the differentiation of the growth rings in conifer wood is the increase in thickness of the cell wall, and reduction of the diameter of the lumen (inner space), from the beginning to the end of the growth ring. In the earliest stages of growing, sap conduction is the dominant function. Hence, the earlywood is present as thin-walled wide lumened tracheids. As the end of the growing period is approached, the cell wall becomes thicker, with a narrower lumen. Stem support seems now to be the most important function. Actually, earlywood and latewood are sources of anisotropy between the radial and tangential planes.

In many species, the cross section of a stem does not have a uniform colour, and it can be divided into two distinct zones defined in terms of how much or how little they contribute to the day-to-day growth of the tree. The wood at the centre of the stem is often harder and darker in colour than the wood near the bark because the stem composed mostly of dead or inactive cells containing toxic extractives which give rise to dark colour and are responsible for resistance of this wood to attack by micro-organisms (Wilcox, 1973). This darker central region is known as heartwood and its cells are dead and physiologically inactive having neither a conducting nor a storage role. The outer part of the stem is known as the sapwood and is physiologically active in the conduction of mineral solutions from the root to the foliage of the tree.

In the sapwood disaccharides are produced and are later transported downward in the inner bark for cell formation and growth[1]. The sapwood lacks toxic extractives, and has low resistance to attack by micro-organisms. Usually sapwood is paler in colour than the heartwood (e.g. pine, Douglas-fir, redwood, hemlock, and *Cupressus*) although in some species (e.g. ash, fir, poplar and spruce) the heartwood is also quite pale. The cells of the heartwood are darker in colour on account of the enrichment of the cells by various extraneous chemicals known collectively as extractives. These chemicals permeate both the cell wall and the cell lumen, and play an important role in slowing down the natural decay of wood by fungi. Heartwood is more difficult to dry and is more difficult to penetrate with preservatives than sapwood.

[1] The distinction of heartwood and sapwood is a functional one. As the diameter of the main stem (and of the branches and roots) increases with growth, the older growth rings gradually stop participating in the life processes of the tree. They no longer take part in translocation and storage of food, but provide only mechanical support. This functional change is associated with physiological, structural, and chemical changes. Heartwood starts forming in older growth rings near the pith, therefore, its diameter normally decreases from the bottom of the tree upward. The relative amounts of heartwood and sapwood within a tree differ according to species, age, and environment of growth.

Characteristics of Radial Surface

A radial surface is produced by sectioning a stem through its pith. The various features e.g. pith, growth rings, earlywood and latewood, heartwood and sapwood, inner and outer bark, appear as longitudinal strips, but some (pith, sapwood or heartwood, bark) may not be represented in a given sample depending on its location. Resin canals (and gum canals) when present show as fine longitudinal lines or indentations of different colour. The rays run at right angles to the longitudinal axis. In woods possessing wide rays, these appear as large, conspicuous flecks.

Characteristics of Tangential Surface

A distinctly different picture is presented by sectioning wood at a tangent to the growth rings. The tangential surface has a more or less pronounced wavy appearance, depending on the colour contrast between earlywood and latewood. The pith is not exposed, but all other macroscopic features may be represented. The rays are cut transversely and they may be conspicuous to the naked eye or difficult to see even with a hand lens.

2.4.2 Microscopic Structure

A more detailed look with the microscope reveals that wood has a cellular structure composed of different types of cells. Their distribution appears unequal depending on the plane which is selected for observation: either transverse, tangential or radial. In the softwoods, the wood structure varies between species and to some extent within species and individual trees (Wilcox, 1973; Desch and Dinwoodie, 1996). The wood is made up of several different types of cells and, generally, softwood structure is less complex than that of hardwoods which have more cell types.

Wood is built up of two main structural components (Figure 2.2) (Wilson and White, 1986), and in some conifers are also found what may be considered a third component. Those present in greater number are tracheids, which lie predominantly in the stem (longitudinal) direction, and are responsible for both supporting and conducting roles. A few tracheids may occur in the radial direction in some species, together with small block-like cells, known as parenchyma[1]. In some softwood species resin canals[2] occur both in the longitudinal and radial directions.

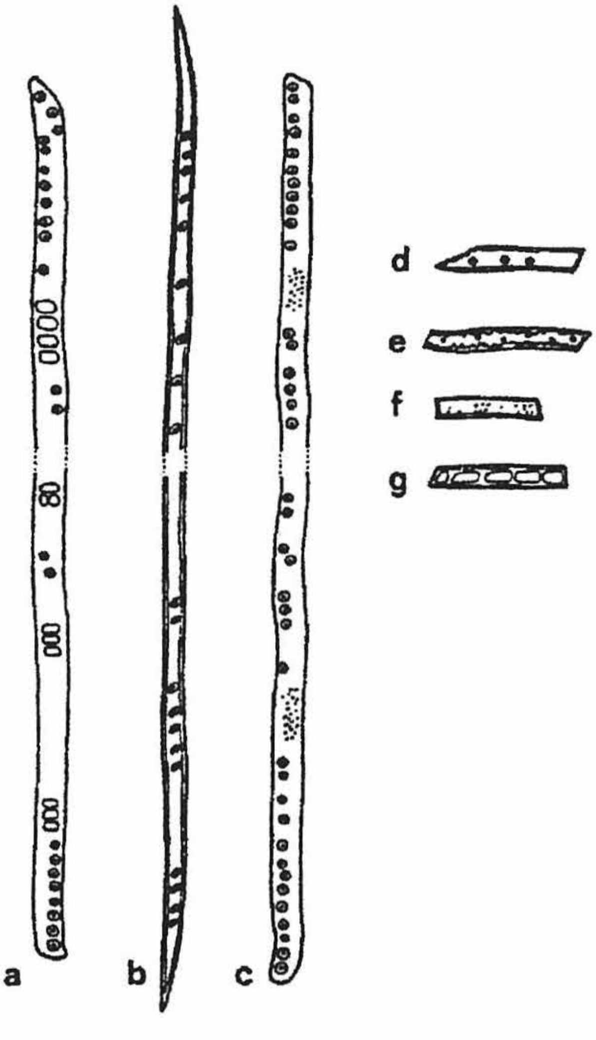


Figure 2.2. Cells of softwood trees: (a) earlywood and b) latewood pine tracheids, (c) earlywood spruce tracheid, (d) spruce and e) pine ray tracheids, (f) spruce and (g) pine ray parenchyma cells (from Sjöström, 1993).

[1] Parenchyma cells (PC) present a thinner wall and are located mostly in the rays. The region where PC are alive defines the sapwood.

[2] They are tube-like cavities whose walls are formed by epithelial parenchyma cells.

Tracheids

The majority of softwood volume is composed of longitudinal tracheids. These are long, fibrous, pointed cells (Butterfield, 1993). They are tube-like, hollow and needle shaped, packed closely together resembling a honey comb in cross section (Dinwoodie, 1981). The cells have closed ends and have relatively short lengths depending on species and position in the stem (Tsoumis, 1991).

As in other cells, the dimensions of the tracheids vary depending on genetic factors and growth conditions. Variations exist among different species and individuals as well as between different parts of the stem and within one and the same growth ring. The tracheid length in the stem increases from the pith toward the cambium and reaches a maximum at the middle of the bole.

Generally, in mature wood the tracheids range between 2 and 5 mm in length and are about 100 times longer than they are wide. Butterfield (1993) estimated their diameters for latewood and earlywood to about 15 and 60 μm, respectively.

Tracheids in the latewood or in narrow annual rings are usually 10 per cent longer and narrower than those formed more rapidly in the earlywood. The tangential width of the tracheids varies only slightly but large differences exist in the radial direction between earlywood and latewood tracheids. Sjöström 1993) mentioned that the average length of Scandinavian softwood tracheids (Norway spruce and Scots pine) is 2 - 4 mm and the width in the tangential direction is 20 - 40 μm. The cell wall thickness of earlywood and latewood tracheids is 2 - 4 μm and 4 - 8 μm, respectively.

The cell wall thickness variation between earlywood and latewood has an effect on density. Wilson and White (1986) stated that latewood often may be 3 or 4 times denser than earlywood. This results in a series of concentric zones of lesser or greater density cell wall substance which are the growth or annual rings (Wilcox, 1973).

Rays

All woods also possess rays which appear on both transverse and radial sections as horizontally lines extending radially in the general direction from the pith (primary rays) to the cambium and continue into phloem (bark) (Kollmann and Cote, 1968). Secondary rays are initiated between these and extend from their inner origin to the bark. Rays are very fine and sometimes difficult to distinguish even with a hand lens. They may appear as a line of several cells stacked on top of each other but one cell wide in tangential-longitudinal section and are termed uniseriate or as several cells wide, termed multiseriate. In radial longitudinal section they appear as sheets of tissue in which the cells are arranged like bricks in a wall (Wilson and White, 1986).

Their combined void volume usually ranges from 6 to 8 percent of the total. Most of the wood rays occur in single rows. Some of the wood rays in softwoods such as the pines contain horizontal resin canals. Wood rays of this type are known as fusiform wood rays.

They are predominantly parenchymatous cells, specialised for food storage, and thus remain alive for longer period of time than prosenchymatous cells which they lose their protoplasm the year in which they are formed. Wood rays (parenchyma) retain their protoplasts for some years and die in transition from sapwood to heartwood. However, rays of some conifers contain prosenchymatous cells i.e. ray tracheids (e.g. *Cupressus*) which are similar to parenchyma but are dead upon maturity (Parham and Gray, 1984). In pines and many other genera, the ray tracheids have a distinctly different appearance to ray parenchyma.

In the cambial zone, division in the ray initial is less frequent than in the fusiform initials (Wodzicki and Brown, 1973) so that ray cells are radially elongated reaching lengths of some 3-7 times the radial width of adjacent axial tracheids (Wilson and White, 1986). Parham and Gray (1984) stated that with or without ray tracheids, generally, softwood rays are uniseriate but some softwoods may have multiseriate rays.

Resin Canals

The remaining percentage of the wood volume (after tracheids and rays) is resin canals (or ducts) which are randomly interspersed continuous tubes among the tracheids. Kollmann and Cote (1968) described axial resin canals as long, tubular channels or cavities surrounded by epithelial tissues (parenchymatous cells which are thin or thick walled) which secrete resins into canals. They are surrounded by one or more layers of epithelial cells. Resin canals build up a uniform channel network in the tree. They form an inter-communicating system of vertical and radial passages in certain softwoods (Jane, 1956; 1970; Bosshard and Hug, 1980; Parham and Gray, 1984).

A number of coniferous woods have resin canals as normal anatomical features (e.g. *Larix, Picea, Pinus*). Normal resin canals occur in rays (fusiform rays) of certain genera, but some resin canals occur as a result of injury called traumatic canals which of these are usually restricted to axial occurrence (Kollmann and Cote, 1968).

In general, resin canals are ineffective for movement of liquids and gases over any appreciable distance in softwoods, despite the fact that they are continuous. This is because they are almost always clogged with resin. Resin canals, which appear to the naked eye or under a hand lens as small, dark or whitish dots, normally occur in wood of pine, larch, spruce, and Douglas-fir. They are generally more numerous and relatively larger in pine species, i.e. pine wood contains more and larger resin canals than does spruce wood.

2.4.3 Ultra-structure

In all species of timber the cells which compose the axial system and the cells of the ray system are tightly integrated to produce a rigid material. The strength properties of wood are determined by the thickness of the cell walls and the microfibril angle. Additionally, the elongate nature of the axial cells which make up the greatest proportion of the cell types present also makes a significant contribution to strength. In contrast, the ray cells have little strengthening function either in the living tree or in commercial timber because of their radial elongate nature. However, they are important in restraining wood under swelling conditions.

Cell Wall Layers

Under high magnification with light microscopy various layers can be recognised in the wood cell walls. A clear demarcation between the individual layers can be seen with the electron microscope (Fengel and Wegener, 1989). Details of the current image of the cell wall, especially its history, are described elsewhere (Wardrop, 1964; Harada, 1965; Cote, 1968; 1977; Preston, 1984).

Tracheid cell walls have a complex structure and are composed of primary and secondary wall layers (Eaton and Hale, 1993). Between the individual cells there is a thin layer, the middle lamella, which glues the adjacent cells together to form the tissues. The middle lamella and adjacent primary wall are often termed the compound middle lamella (Fengel and Wegener, 1989).

The primary wall is very thin (about 0.1 µm) compared to the thick secondary wall (about 10 - 12 µm). This double layering is almost universal in wood cell walls except in the ray parenchyma cells of certain families of conifers e.g. Taxaceae or Araucariaceae which have only a primary wall and a protective layer (Eaton and Hale, 1993).

The thick secondary wall is further sub-divided into three layers - the S1, S2 and S3. The S1 and S3 are thin, about 1 µm thick in latewood (Siau, 1971). The S2 layer is much thicker varying from 1 µm - 10 µm in thickness depending whether the tracheid from earlywood or latewood (Siau, 1971). This has a significant effect on the physical and the mechanical properties of wood. In each cell wall layer there are differences in the chemical composition and different orientations of the structural elements (Fengel and Wegener, 1989). The walls of the wood cells are composed of three types of structural substances (chemical constituents) which Wardrop (1964) classed as framework, matrix and encrusting materials (Kollmann and Cote, 1968).

Cell Wall Pits

The cells constituting the wood are interconnected by pits, which enable the passage of fluids, through porous membranes, in both horizontal and vertical planes. With these interconnections, water or chemical solutions can reach the bulk of a block of timber. Panshin *et al.*, (1964), Fengel and Wegener (1989) and Eaton and Hale (1993) mentioned two principal cell wall pits that occur in softwood as simple pits (between two parenchyma cells) or bordered pits (between two tracheids). Panshin *et al.* (1964), also reported a third kind (in fact a combination of simple and bordered pits) called half (semi) bordered pits (between an axial tracheid and a parenchyma cell).

Generally, they connect adjacent axial cells, adjacent ray cells and contiguous axial and ray cells. All pits have a membrane positioned more or less mid-way along the pit canal between two adjacent cell walls, and when complementary pits in the walls of two neighbouring cells are connected the whole is called a pit pair (Eaton and Hale, 1993).

In softwoods the pit is a micro-structural opening in the wood cell wall that acts as a valve. In a living tree, pits play a significant role in providing inter-cell communication for the translocation of liquid, so there must be a complementary pit in the adjacent cell (Kollmann and Cote, 1968).

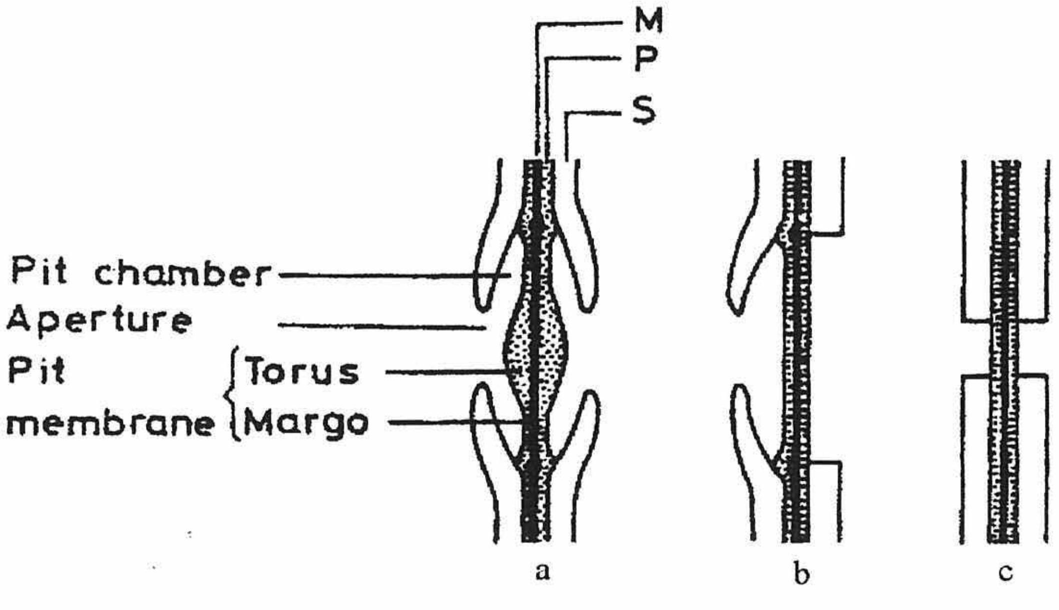


Figure 2.3. Types of pit pairs: (a) bordered pits, (b) half-bordered pits; and (c) simple pits. (M) middle lamella, (P) primary wall, (S) secondary wall (from Sjöström, 1993).

Simple Pits

These are holes in adjacent cell walls, interrupted by a membrane in the region of the compound middle lamella and appear in parenchyma cells (Fengel and Wegener, 1989). Eaton and Hale (1993) said simple pits have a cavity which has more or less uniform diameter along its length. The pit membrane, derived from primary wall and middle lamella of adjacent cells, is made up of loosely-arranged microfibrils which have fine cellular strands called plasmodesmata that extend through.

Simple pits ensure communication laterally between a ray tracheid and a ray parenchyma and occur at points where wood rays come in contact with longitudinal tracheids, as seen in radial section. Panshin *et al.* (1964) mentioned that these are rectangular areas, formed by walls of ray cells and longitudinal tracheids, and are called crossfield pits. Phillips (1948) recognised diversity of these crossfield pits and described them as fenestriform (window-like), pinoid, piceoid, cuppressoid, and taxodioid, according to their appearance.

Bordered Pits

These pit pairs are generally found between conductive cells (e.g. longitudinal and ray tracheids; Siau, 1971) and those leading laterally from one longitudinal tracheid to an adjacent tracheid (Panshin *et al.*, 1964). The holes in both cell walls enlarge towards the pit membrane forming a cavity (Fengel and Wegener, 1989).

Inside the pit chamber is an intermediate membrane positioned longitudinally across the chamber, called the torus (a thickened cellulosic disc). The membrane surrounding the torus is called the margo or supporting membrane and it consists of microfibrillar strands radiating from the torus to the annulus at the periphery of the pit chamber. The torus is lens-shaped in latewood (Liese and Bauch, 1966), often encrusted (Petty, 1970), and the aperture of the pit is elliptical in shape making it difficult for the torus to seal it (Bailey, 1965).

The number, size and shape of bordered pits varies between earlywood and latewood tracheids. Panshin *et al.*, (1964) stated that in earlywood they are large and numerous on the radial faces of the longitudinal tracheids and much smaller and restricted to last few rows of the latewood on the tangential walls. On the radial walls pits are arranged mostly in a single row, occasionally they are found in pairs in the earlywood tracheids. Inter-tracheid bordered pits on the radial walls are most numerous towards the end of the tracheids and are sparse or absent over extensive areas through the central portion of the cell. In longitudinal tracheids the bordered pits are along the tapered portion of the radial surfaces (Siau, 1971), and the number of pits per tracheid varies from 50 - 300 in earlywood with fewer in latewood (Stamm, 1964). In spruce, the tracheid length ranges from 1.2 - 7.5 mm (Siau, 1971).

Comstock and Cote (1968) stated that latewood cell walls have greater thickness, a correspondingly deeper pit structure thickness, and a more rigid pit membrane thickness. Latewood pits are known to have a smaller diameter (Liese and Bauch, 1966; Comstock and Cote, 1968) with one study finding latewood pits to be about 10 μm in diameter whilst those of earlywood are in the range 15 to 20 μm (Petty, 1970). In Corsican pine, Eaton and Hale (1993) described the diameter sizes of the chamber as 20 μm and aperture as 6 μm for earlywood compared to chamber 6μm and aperture 2 μm in latewood. Siau (1971) generally reported the over all diameter of pit chamber of coniferous bordered pits as range from 6 - 30 μm, latewood pits being smaller than earlywood.

Semi-Bordered Pits

These belong to pit pairs which occur at points where ray parenchyma cells come into contact with longitudinal tracheids. In softwoods, half (semi) bordered pits have a central thickening at the tracheid side (Harada, 1964).

A special form of these pits are the fenestriform or pinoid pits between ray parenchyma cells and longitudinal tracheids with large membrane, large apertures and small borders (Thomas and Nicholas, 1968; Fengel, 1970). Panshin *et al.* (1964) further described the shape as round or square with slightly bordered indistinguishable except under high magnification.

Pit Aspiration

In coniferous trees sapwood water is known to move longitudinally through the tracheid lumina, passing from one tracheid lumen to the next through the bordered pits (Bailey, 1913). The same pathway is used by preservative liquids when penetrating wood from a transverse surface. Because tracheid lumina provide an unobstructed pathway for flow it follows that the bordered pits will largely control the movement of fluids in conifer wood (Petty, 1970a).

The structure of a typical earlywood bordered pit is shown in Figure 2.4. In green wood water may pass from one pit aperture to the other through the pit chamber and the pit membrane pores. When wood is dried the structure (shown in Figure 2.4a) may be modified by the process of aspiration in which the torus moves across the pit chamber to seal off one of the pit apertures, thus preventing fluid flow through the pit (Figure 2.4b).

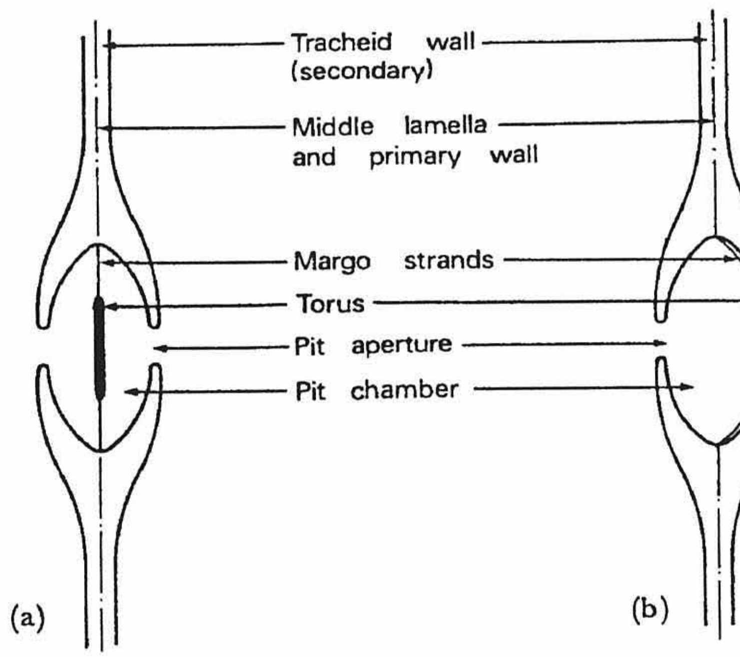


Figure 2.4. (a) Diagrammatic representation of an earlywood bordered pit in section transverse to the pit membrane. Typical dimensions and primary (P) and secondary (S) cell wall layers are indicated. (b) Aspiration of a bordered pit during drying. The torus is pulled across the pit chamber by surface tension forces (from Petty, 1970a).

It has been suggested that aspiration is caused by the surface tension forces in the last drop of water to be evaporated or pulled from the pit which draw the membrane across the pit chamber (Phillips, 1933), but this may not be the only factor involved because Comstock and Cote (1968) stated that rigidity or stiffness of the pit membrane and adhesion of the torus to the pit border also are regarded as being concerned in pit aspiration.

Capillarity and the related surface tension of the withdrawing liquid water force the pit membrane and torus against the pit opening, causing aspiration (Liese and Bauch, 1966; Hart and Thomas, 1967; Bamber and Fukazawa, 1985; Johansson and Nordman-Edberg, 1987). Hydrogen bonding between the pit opening, the margo, and hydrophobic extractives contribute to the irreversibility of pit aspiration (Bamber and Fukazawa, 1985; Johansson and Nordman-Edberg, 1987).

Due to differences in structure, in latewood the forces necessary for closing the pits are higher, so that even the high surface tension of water is not sufficient to bring about aspiration of many of the pits in these tracheids (Liese and Bauch, 1966; Comstock and Cote, 1968). The relative rigidity of the pit membrane compared to the surface tension forces will determine whether the torus is displaced sufficiently from the central position to come into contact with the pit border (Comstock and Cote, 1968). Ray tracheid bordered pits presumably do not aspirate due to their size.

Some studies have concluded that pit aspiration is an irreversible process (Krahmer and Cote, 1963; Johansson and Nordman-Edberg, 1987) because an increased adhesion might occur after pit aspiration due to hemicellulose or pectic-like substances producing a gluing effect (Liese and Bauch, 1967). Experiments with rewetted wood by Kumar and Morrell (1989) support this.

The role of water in the adhesion process appears to be an overriding factor which provides the molecular forces necessary for adhesion to occur (Comstock and Cote, 1968). Forces involved are thought to include hydrogen bonding and Van der Waals forces.

Some regions of a specimen may be less susceptible to aspiration than others. A torus aspirated against a wart-covered pit border could reduce the permeability of the pit, but possibly not stop it completely (Krahmer and Cote, 1963).

Bolton and Petty (1978) further said that the total pressure differential can aspirate pits and cause cessation to flow. This is due to pit membrane deflection and they found this phenomenon higher in latewood than in earlywood. Earlier workers (Gregory and Petty, 1973) noticed that when a pressure differential is established across the pit membrane the torus deflected towards one of the pit borders.

The method of drying timber can alter penetration properties. Petty and Puritch (1970) found permeability of solvent dried specimens was much greater than air dried specimens. In solvent drying, a low surface tension solvent (e.g. pentane) prevents pits from being aspirated.

A pressure of 214 lb/in^2 (14.75 bar) must be applied to force a liquid/gas interface through a capillary of 0.1μm radius, which is a typical value for pit opening (pit margo pore) (Siau, 1971), although in practice lower pressures are often used.

Spolek and Plumb (1981) also said menisci formed between liquid/gas (i.e. water/air) in the tracheid lumens will control the magnitude of capillary pressure. The magnitude of the capillary pressure forces is dependent on three factors; liquid surface tension, interfacial contact angle and pore radius. These can attain values of several bar in wood, where pores of radius about 0.1μm are often encountered (Petty, 1970; Smith and Banks, 1971).

2.5 Wood Density in Sitka spruce

2.5.1 Wood Density and Void Volume in Sitka spruce

Density, used here synonymously with specific gravity, is a measure of a quantity of cell wall material contained in a certain volume of the piece of wood and is an index of void volume (Hughes, 1967; Tsoumis, 1991). It is calculated as the ratio of dry weight of wood to its volume and is measured in units such as kilograms per cubic meter. On the other hand, void volume is the amount of empty/air spaces composed by cell cavities and intercellular spaces in a given volume of wood, and thus Siau (1971) defined porosity as fractional void volume of wood.

Without cavities and intercellular spaces the relative density of the cell wall materials is practically constant for all timbers having a specific gravity of 1.53 gcm^{-3} on oven dry mass and volume basis (Dinwoodie, 1981; Tsoumis, 1991), i.e. a cubic metre of solid wood would weigh roughly 1500 kgm^{-3}.

The density (1.53 gcm^{-3}) is the physical value for an ideal lignified cellulosic cell wall which is completely non-porous. The actual value may vary slightly between species and between earlywood and latewood as the proportion of the cell wall constituents varies, i.e. the density of cellulose, hemicellulose and lignin are roughly 1600, 1500 and 1400 kgm^{-3} respectively, and the amount of void space within the oven-dry cell wall is small, *ca.* 4 % of total weight (Weatherwax and Tarkow, 1968). Extractives may also make a significant contribution (Tsoumis, 1991).

Importantly, cell wall substance adsorbs and desorbs moisture from and to the environment because wood is a hygroscopic material. A consequence of this is that cell wall shrinks and swells, thus the relative proportions of cell wall substance and pore space vary greatly, Therefore, some variation in values is expected from the basic density which tends to vary significantly between species, within species, between trees, and also within single trees. This is influenced by how well microfibrillar lamellae pack together.

2.5.2 Importance of Density on Wood Properties of Sitka Spruce

Wood is biological material with remarkable variability in its quality, e.g. wood structure, density and other associated properties. The general systematic trend accepted for variation in specific gravity is a high value close to the tree apex followed by a decrease to a minimum and a constant or slight increase towards the base. This pattern is often found to be the inverse of the pattern obtained for ring width (Brazier, 1970; Denne, 1979). Some exceptions however have been observed, for example in Sitka spruce, Elliott (1966) found no systematic variation from apex to base.

For a single species, wood quality varies not only from tree to tree (intertree) but also within trees (intratree). The intratree variation is the major source of variability (Kandeel and Bensend, 1969) in wood quality (Panshin and de Zeeuw, 1980; Zobel and van Bujitenen, 1980; Wilson and White, 1986). Variation in wood quality makes it difficult to predict precisely the performance of timber and therefore process and utilize it efficiently. It is known that wood quality can be controlled by genetic and silvicultural means (Denne and Dodd, 1980). It is generally agreed that research into quality improvement should aim at identifying favourable genotypes and also growing conditions which will produce wood of the desired quality. Density is considered one of the most important indices of timber strength properties (Bendtsen, 1978) since it has been positively correlated with such properties as modulus of rupture (MOR) and modulus of elasticity (MOE), maximum crushing strength, hardness and shrinkage (Brunden, 1964; Fielding, 1967), and it also has a considerable influence on machinability, conversion, acoustic properties, and wearability (Harris, 1969; Walker, 1984).

2.5.3 Methods of Density Determination

Density is primarily determined by the amount of cell wall material in relation to the voids (Bumber and Burley, 1983), so the density determinations are influenced by the amount of moisture in the wood (Barley and Burley, 1983; Siau, 1984). Thus to be meaningful the amount of moisture in the wood must be indicated or specified with the density figure.

Density is usually expressed in one of the following ways: green, at the same moisture content as in the living tree; oven-dry, after heating in an oven at 103 °C until constant mass is achieved; air-dry, at equilibrium with ambient conditions or at some other specified condition; basic density (oven dry mass divided by green volume) is a standardised method which enables comparisons of different specimens to be made free of variation due to shrinkage.

The mass of a block is readily determined by weighing but the measurement of the volume of a specimen presents more problems. It is possible to measure the linear dimensions of a regular shape piece of wood cut from a plank, and then calculate its volume, but this is rarely convenient, and might be impractical if only a tiny sample is available e.g. archaeological specimen. There are a variety of other ways volume can be measured such as densitometry, gravinometry, pycnometry, dot-count, microphotometer, maximum moisture content method and the archimedian method (Breese, 1990). The most appropriate method for this study is the maximum moisture content method.

Maximum Moisture Content Method

A useful way of determining the volume of an irregular block is by using the cell wall density, i.e. 1.53 gcm^{-3}. The method of determining basic density based on this is known as the maximum moisture content method and has been evaluated by Smith (1954) who derived the following formula;

$$d = [Mo / \{(Mo / G) + Ms) - Mo)\}] * 1000 \quad (2.1)$$

where d = basic density (kgm^{-3}), Ms = saturated mass (g), Mo = oven dried mass (g), G = specific gravity of cell wall substance which is taken to be 1.53 gcm^{-3}.

In this method, only two weighings are required to determine the basic density, i.e. saturated and dried. Wood must fully be saturated by water to measure the real volume according to the Archimedes principle since a completely saturated wood block displaces an amount of water which equals its own volume (Olesen, 1971). The maximum moisture content method is commonly used by researchers on account of its accuracy.

2.6 Determination of Growth Ring Width Characteristics

It is useful to know annual ring structure and density distribution when studying the quality of wood, grading it, or determining how its structure affects other parameters, e.g. residual flow in softwoods with a high proportion of high earlywood pits aspiration on drying. Density is directly affected by the proportion of cell wall substance to lumen, since the density of the cell wall material itself varies hardly at all (Tsoumis, 1964; Scaramuzzi, 965; Fielding, 1967; Kellogg and Wangaard, 1969).

Since tracheids account for about 90% of the wood volume in softwood (Scaramuzzi, 1965) density is likely to depend on both the diameter and wall thickness of the tracheids (Denne, 1979; Lewark, 1986; Thompson, 1992; Simpson, 1993; Mitchell, 1995) and on the proportions of earlywood to latewood.

The proportion of earlywood to latewood is a further factor influencing wood density; a high correlation between latewood percentage and density for example, has been repeatedly demonstrated this century. In *Pinus contorta* the latewood percentage has been reported to increase with cambial age, thus increasing the density of the mature wood (Harris, 1971; Pearson and Gilmore, 1980; Fries, 1986); this trend has also been noted in *Pinus taeda* (Megraw, 1985). In addition, the mean wall thickness of latewood tracheids has also been reported to increase with distance from the pith, whereas the same parameter in earlywood tracheids tends to remain constant (Schultze-Dewitz, 1965). With a longer growing season, the latewood proportion would also generally increase, again resulting in an increased density; however, a vigorous growth rate would generally result in a larger proportion of earlywood with larger lumens (Thompson, 1992).

Further, it has been observed that radial tracheid diameters across wide growth rings are not only larger, but also more constant in size for most of the ring *(the plateau phase)* before declining sharply at the latewood (Briand *et al.*, 1993). In less vigorous trees, having narrow rings, radial tracheid diameter in the earlywood has been reported to be smaller and the plateau phase much shorter or absent, there being a gradual decline to the latewood. These trends usually result in an inverse relation between growth rate and density, and so breeding programmes which are currently producing trees of faster growth with small diameter branches, may consequently tend to produce trees of reduced density (Maun, 1992). Thompson (1992) however, indicated that increased vigour does not automatically result in lower density and this suggests a great genetic potential for selecting vigorous trees with acceptable density values.

2.7 Factors Affecting Permeability in Softwoods

The cause of this variation has been established by many authors (e.g., Smith, 1963; Hunt and Garratt, 1967; Bailey and Preston, 1969; Banks, 1970; Petty, 1975; Siau, 1984; Eaton and Hale, 1993).

Nicholas (1972) stated that the successful treatment of wood is basically dependent on three factors; a) wood characteristics, b) types of treating processes and (c) characteristics of treating solutions.

2.7.1 Wood Characteristics

Permeability in Relation to Darcy's Law

Permeability is defined as the ease with which fluid flows through a porous medium under the influence of pressure gradient (Langrish and Walker, 1993). Fick's first law of permeability stated that (Permeability = Flux / Gradient), in which Flux is the rate of flow per unit cross sectional area expressed in [(cm^3 fluid) / (cm^2 area) / sec] and Gradient is the pressure difference causing the flow per unit of specimen length in the flow direction (Siau, 1971).

Several mathematical models have been used to describe this process. Simple models treat wood as pipes (Darcy, Hagen-Poisseuille) but non-steady state flow occurs and rates of flow decrease with increased specimen length and length of treatment time (Hudson and Henrikson, 1956; Petty, 1970; Bramhall, 1971). This may be attributed to the formation of air bubbles in the structure, and the effect of a number of blocked flow pathways (Erickson and Estep, 1962; Kelso, 1963; Banks, 1981). An essential detail shown, e.g. in the Hagen-Poisseuille equation given below, is that flow rate is proportion to the fourth power of the capillary or pore radius so that flow is markedly affected by pore or capillary size (Eaton and Hale, 1993). Flow through capillaries is dependent upon capillary size and arrangement. The volume of liquid flow per unit of time increases directly as the fourth power of the radius and inversely as the length of the capillaries decrease (Stamm, 1946).

$$Q = \pi r^4 \Delta P / 8 \eta l \qquad (2.2)$$

where, Q = volume rate of flow, r = capillary radius, ΔP = pressure difference, η = liquid viscosity, l = capillary length

Effect of Density

There must be sufficient space within the wood to accommodate the desired volume of preservatives, for instance wood must have adequate porosity. Additionally, it must have low moisture content before treatment otherwise this porous space is occupied by water (Richardson, 1978). Generally, porosity of most commercial species is not a limiting factor in wood treatment unless the free moisture content is excessively high (Siau, 1971). There is thus a limit as to the size of void volume (porosity) and to the total amount of liquid which the block of wood can absorb (Tiemann, 1944). The maximum absorption is thus a function of density or void volume (Kollmann and Cote, 1968) or as stated by Nicholas and Siau (1973) the porosity or fractional void volume of wood determines the maximum amount of treating solution that can be injected into the structure. Thus there is a correlation between density and depth of penetration.

However, Erickson *et al.* (1938) pointed out that there is no such correlation and said some high density woods (e.g. beech and red oak) are permeable while many light woods are refractory (e.g. heartwood of Douglas-fir). Koch (1972) also stated that wood with high specific gravity (density) is easier to penetrate, although (when treated to refusal) wood with low specific gravity usually retains more preservative. Density has also been related to preservative retention. Mc Quire (1975) for example found that wood (radiata pine) with a basic density greater than 0.5 gcm^{-3} failed to meet retention specification when treated under normal preservation schedules. Therefore, differences in density were suspected as a possible source of variation of preservative retention (Taylor, 1991).

2.7.2 Effect of Pressure

In pressure impregnating methods it is the amount of pressure (pressure differential) which is said to be one of the important factors governing the flow, although other treatment factors are of prime consideration including fluid viscosity, solvent contact angle, wood pore radius and wood capillary length (Eaton and Hale, 1993).

Various things may happen inside the wood that affect penetration depending upon rapid or slow pressure applications: (i) pits either become blocked or blocked pits break open due to high pressure, (ii) fluids move into pits effectively under slow pressure or (iii) air bubble menisci (fluid-air interfaces) retard movement of fluid.

The amount of pressure used and the period of time over which it is applied are both significant factors in the impregnation of wood. The intensity and duration of pressure that will be best suited to a given treatment of wood is difficult to determine accurately. It is dependent upon a variety of factors which include the absorption and penetration desired, the ease with which timber can be impregnated and the temperature (which affects the viscosity) of the preservative. As a general rule, the treating period should be as long as practicable, and the intensity of pressure so regulated to ensure the desired absorption and retention. Further, moderate pressures and reasonably long periods of impregnation give better results than very high pressures and short treating periods. Penetration obtained under the latter conditions are likely to be erratic and absorption and retention may also be unsatisfactory. Prolonged treating periods are particularly significant when impregnating refractory timbers (Hunt and Garratt, 1967).

There are reports that slow application of pressure is of importance to achieve good preservative penetration and retention, e.g. with creosote (Personal Communication to Calders and Grandidge, 1994). In this case, this may be due to a heat transfer requirement and the cooling effects by wood on creosote viscosity during initial ingress. Alternatively, some reported rapid pressure application and/or fluctuating pressure application is said to be beneficial to preservatives with rapid fixation characteristics as the preservatives are carried at a faster rate into the wood capillary system (Hudson and Henriksson, 1956).

Bailey (1965) reported that if a specimen is subjected to a relatively low pressure, e.g. 15 lb/in^2 (1 bar), the radial flow rate could be constant for 15 - 20 minutes, whereas, if the first applied pressure was relatively high e.g. 60 lb/in^2 (4 bar), the flow rate decreases with time. On the other hand, if the higher pressure was approached in steps of 15 lb/in^2 (1 bar), a constant flow rate could be observed at each successive pressure (Bailey and Preston, 1970b).

Penetration increases with increasing pressure and with decreasing viscosity. Apparently, relatively high pressures can force liquid into low permeability (refractory) wood specimens (Siau and Shaw, 1971). MacLean (1924) using treating pressures from 100-250 lb/in^2 (6.6-16.6 bar) found that as pressure increased the penetration and absorption were likewise increased with treating periods from 2-8 hours. He also showed that the penetration generally varies more nearly proportional to pressure than to square root of pressure due to the stretching of the pit-membranes by pressure, thus, enlarging the pores to some extent. MacLean (1927) reported consistent increases of penetration and absorption with increased pressure from 100 - 175 lb/in^2 (6.6 - 11.6 bar). Stamm (1959) using very high pressure observed sufficient filling and penetration of capillary voids with molten metal. Further, Willeitner and Murphy (1987) observed at a constant pressure of 171 lb/in^2 (11.4 bar) and pressure period of 3 hours, there was a slight increase with time in fluid uptake.

Hosli and Ruddick (1988) treated white spruce with CCA (Copper-Chrome-Arsenate) using a pulsation process at maximum pressures of 1.0 to 2.1 MPa (10 to 21 bar), and observed that a rapid change of pressure caused greater pressure differences through penetration obstacles in the wood, such as pits. During this time, the total pressure within the wood slowly increased, thus, allowing the penetration of small pores. Because of the slow increase in the total pressure within the wood, the pulsation process showed great potential for the treatment of spruce with creosote under a pressure of 2.1 MPa (21 bar) (Osusky *et al.*, 1982). It has also been shown that some refractory woods are well treated by very high pressure (>255 lb/in^2, 17 bar) applications: for instance, Siau (1970a) showed heartwood of Douglas-fir and white oak almost fully impregnated with oils at high pressure.

2.7.3. Effect of Treating Solution

Certain properties of liquids may have significant effects on flow rate in wood e.g. non-polar liquids have significantly higher flow rate than polar liquids (Buckman, 1935; Erickson *et al.*, 1937). The swelling effect of water generally decreases permeability due to hydrogen bonding effects (Goring, 1966; Morgan and Purslow, 1972). This may result in molecular turbulence effects at cell wall interfaces (Nicholas and Siau, 1973).

MacLean (1927) mentioned that liquid viscosity affected permeability (e.g. creosote). Rapid penetration can be achieved if viscosity and contact angle are kept to a minimum with surface tension as high as possible (Richardson, 1978).

The contact angle increment between aqueous solution and cell wall affects permeability. Banks (1981) said that penetration within flow paths containing gas may lead to liquid/gas interface to pass through a bordered pit. If walls are still porous higher pressures are required for permeation by an aqueous solution (Petty, 1970). When *Pinus* species are impregnated by vacuum/pressure methods with aqueous CCA preservatives, the solutions pass rapidly through some of the rays and into adjacent axial tracheids (Levi *et al.*, 1970). From these tracheids, the solutions pass into other rays and via bordered pits and possibly cell walls, so that permeable sapwoods of *Pinus* are fully saturated with solution (Bailey, 1913; Schulze and Theden, 1950).

Nicholas (1972) mentioned that ageing processes in CCA preservatives significantly reduce penetrability of treating solution. This ageing is caused by progressive build-up of extractives and chemical reaction products which form colloids and suspensions (particulate matter).

2.8 The Path of Flow

Wood shows anisotrophy of flow and also major differences between heart and sapwood.

2.8.1 Longitudinal Flow

It is widely believed that in longitudinal flow through wood the greatest bulk fluid transport occurs through the bordered pits of the axial tracheids (Buro and Buro, 1959; Erickson and Crawford, 1959; Osnac, 1961; Wardrop and Davies, 1961; Cote and Krahmer, 1962; 1963; Erickson and Balatinecz, 1964; Ernst, 1964; Petty and Preston, 1968). Longitudinal flow in conifers involves a pore system with three components in series, namely: tracheid lumina, pit apertures and pit membrane pores (Petty and Preston, 1969). Some softwoods also possess longitudinal resin canals and parenchyma cells which can function as avenues for flow (Nicholas and Siau, 1973). Generally, the longitudinal flow of softwoods is much greater than the tangential flow, due to the fact that there are fewer pitted cross walls to transverse per unit length in the longitudinal than in the tangential direction (Siau, 1984).

Much research has supported the theory that the bordered pit is the primary structure governing the longitudinal permeability of softwoods (Krahmer and Cote, 1963; Sebastion *et al.*, 1965; Comstock, 1967; Erickson, 1970; Petty, 1970; Keith and Chauret, 1988; Kuroda and Siau, 1988). Bordered pits, especially the torus, receive heavy treatment (Liese and Bauch, 1967; Behr *et al.*, 1969; Greaves, 1974; DeGroot and Kuster, 1986). In spruce, the axial tracheid bordered pits are larger and much more numerous than those on the tangential walls (Baines, 1986).

The largest decrease in permeability occurs in the bordered pit component (Comstock and Cote, 1968; Petty, 1970; Bolton and Petty, 1977) where pit pores contribute more than 90% of the total resistance to liquid flow (Petty, 1970). The hypothesis of membrane displacement alone cannot account for the observed reduction of permeability (Comstock and Cote, 1968; Bolton and Petty, 1977) which is determined by the interfibril spaces of the margo in the bordered pit (Liese and Bauch, 1967). The margo in eastern hemlock (*Tsuga canadensis*) is seen to have a very high porosity (Comstock and Cote, 1968).

Petty and Puritch (1970) showed two structural components offered resistance to flow: tracheid lumina and pit margo pores. Similarly, Bailey and Preston (1970) and Smith and Banks (1971) identified the annulus (margo) and the torus of bordered pits, and tracheid lumina and bordered pit system, respectively. Bolton and Petty (1975) observed the above structures and also reported a third structure, the pit aperture as offering resistance to flow. Although tracheid lumina and pit margo pores are voids, it is the components that make them which resist the fluid movement (e.g. cell wall and torus) and the radius of the pores which is the important factor in determining resistance to flow. The fractional contribution of the lumens to the total flow resistance is less in the refractory softwoods. This is due to the relatively much greater resistance of pit pairs in this direction (Siau, 1971).

The number and location of bordered pits have generally been thought to have an influence on the refractory nature of red spruce (*Picea rubra*). The number of conducting pathways has been discussed; Sebastion *et al.* (1965) estimated the number of bordered pits in the region of overlap of two tracheid ends (of white spruce, *Picea glauca*) to cover a range of 5 to 20. Petty (1970) reported that the mean number of 250 (st.dev. = 30) pit pores per conducting tracheid (*Picea sitchensis*) is very much larger than any of the previous estimates.

Only at the edges of the growth rings do bordered pits exist on tangential walls (Bailey, 1965; Panshin and DeZeeuw, 1980). This may not matter because Liese and Bauch (1967) report that the number of pits in longitudinal tracheids has no significant influence on the treatability of dried spruce (*Picea abies*). Many attempts to correlate porosities with permeabilities found there is no general relationship (Bailey, 1965).

2.8.2 Tangential Flow

Tangential fluid flow is primarily through longitudinal tracheids and intertracheid bordered pits (Erickson, 1970; Keith and Chauret, 1988). According to Petty (1970) it is the pits in the centre regions of the tracheid which are most effective in tangential flow. The total number of pores being used for tangential flow is approximately 10^3 times smaller than the number for longitudinal flow.

In many conifers, tangential penetration is superior to radial penetration. It is facilitated by the continuity of the relatively permeable latewood bands, and to some extent, by predominance of pits in the radial walls of the earlywood tracheids (Siau, 1971).

2.8.3 Radial Flow

The overall contribution to flow by rays and resin canals may be of secondary importance since they form a small fraction of the wood volume. However, when flow into a pole or post is considered the zone treated by longitudinal flow is beneath the ground line so radial flow and penetration is very important.

Rays offer the major flow path in the radial direction (Erickson, 1964) and when present, ray tracheids are usually more effective in conduction than ray parenchyma cells (Buro and Buro, 1959) but reverse has also been found (Wardrop and Davies, 1961). Behr *et al.* (1969) treated softwood with creosote and pentachlorophenol dissolved in aromatic gas oil and found that the preservative (oil) was observed in ray parenchyma and ray tracheids. The passage of oil between ray parenchyma cells and from ray parenchyma cells to longitudinal tracheids was evidence of flow through simple pit pairs and semi-bordered pit pairs, thus, rays were frequently penetrated confirming the importance of rays as a flow path. Nicholas and Siau (1973) also observed that vertical and horizontal resin canals and epithelial cells were generally filled. Wardrop and Davies (1961) showed that the ray parenchyma cells apparently were more easily penetrated than ray tracheids and water-borne preservatives in longitudinal resin canals which also contributed to the flow. The role of resin canals is unclear. Liese and Bauch (1966) stated that the presence of resin canals has no recognizable influence on the permeability, while Erickson (1970) suggests that there is some degree of penetration through resin canals and intercellular spaces. As discussed earlier, the presence of resin within resin ducts may have some influence on this.

There is some evidence that rays may be an important flow path for preservatives since there are bordered pit pairs leading from longitudinal tracheids to the ray tracheids and half bordered pit pairs permitting flow to adjacent ray parenchyma cells. Therefore, most of the radial flow of fluids is probably through the ray parenchyma cells and between the longitudinal tracheids and rays via cross-field pits (Siau, 1984). The location and nature of the cross-field pits are characteristic and used for the identification of different wood species (compare the small elliptic pits in spruce with the large window (fenestriform) pits in Scots pine, Figures 2.2 and 2.5).

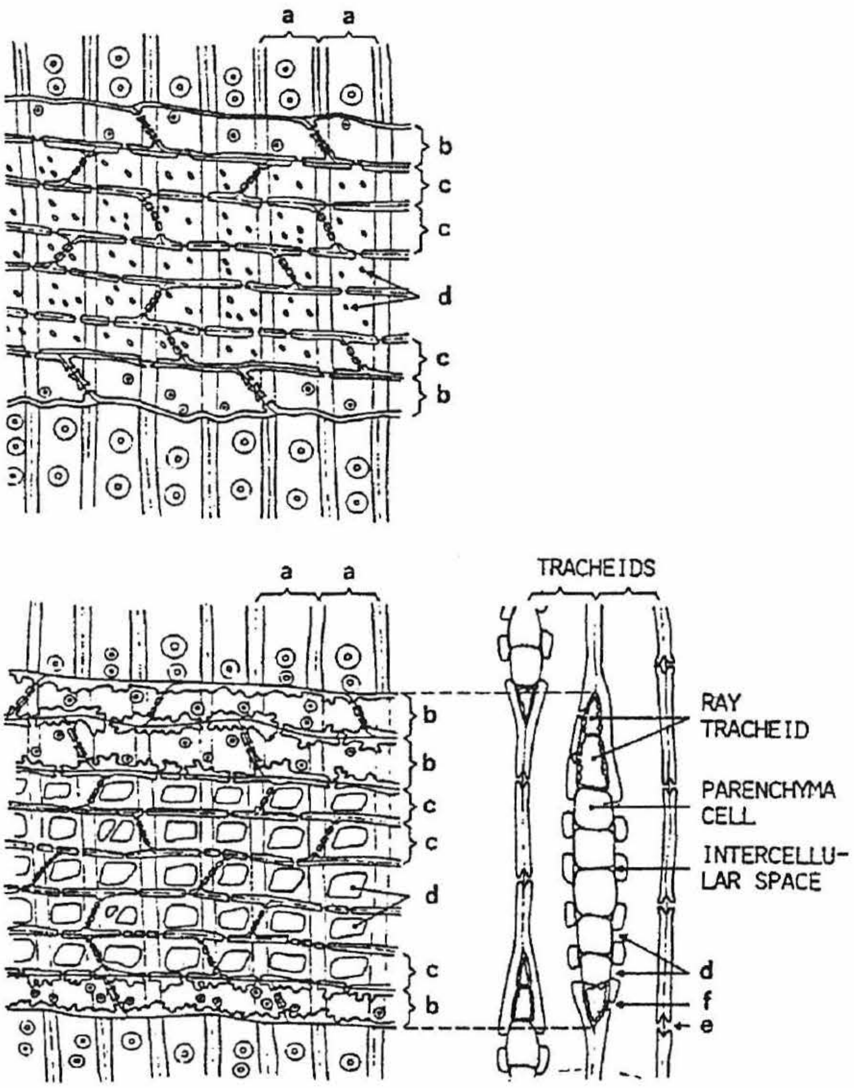


Figure 2.5. Radial section of a spruce ray (above) and radial and tangential section of a pine ray (below). (a) Longitudinal tracheids. (b) Rows of ray tracheids (small bordered pits). (c) Rows of ray parenchyma. (d) Pits in the cross fields leading from ray parenchyma to longitudinal tracheids. (e) A bordered pit pair between two tracheids. (f) A bordered pit pair between a longitudinal and a ray tracheid (from Iivessalo-Pfäffli, 1967).

If there were no flow through the rays, the tangential permeability would exceed the radial because most of the pits are on the radial surfaces of the tracheids rays. However, Banks (1970) has found the radial permeability of *Pinus sylvestris* wood to be greater than the tangential permeability, and has concluded that this is due to flow through the rays and that it explains the superior treatability of this wood when compared with *Picea abies*.

Ray cells (including ray tracheids) are known to be much better treated than longitudinal tracheids (Liese and Bauch, 1967; Greaves, 1974; DeGroot and Kuster, 1986) and cross-field pit membranes are also well treated (Greaves, 1974; DeGroot and Kuster, 1986). Liese and Bauch (1967) suggest that the main reason for the limited radial penetration of spruce (*Picea abies*) is the relatively small proportion of ray tracheids, which they regard as the main radial pathways. The ray tracheids of spruce have unaspirated bordered pits even when air dry, but they are heavily encrusted in the heartwood, which limits fluid penetration (Baines and Saur, 1985; Baines, 1986).

In a study of Sitka spruce (*Picea sitchensis*), the conducting ray tracheids were found mainly in the latewood (Petty, 1970); but in white spruce (*Picea abies*), the radial movement of CCA was definitely restricted to the latewood (Keith and Chauret, 1988).

In softwoods, ray parenchyma cells are noted as often lacking preservative treatment. This is because ray parenchyma cells communicate with each other only through small channels (simple pits) of a few microns in diameter blocked by a separating membrane through which only very small plasmodesmata pass (Liese and Bauch, 1967). Ray parenchyma have small simple pits connecting them to the tracheids and the ray cells are connected by small plasmodesmata and not by the pits, which could explain why the ray tracheids surrounding the ray parenchyma cells are often penetrated by the preservative, while the parenchyma is not penetrated (Baines and Saur, 1985; Baines, 1986). In addition, the impermeability of the parenchyma cells is said to be due to the impervious protoplasmic debris which lines the walls (Bailey, 1965). Contrary to other studies, Krahmer and Cote (1963) suggest forced penetration parallel to the rays indicated that penetration proceeded to a greater extent in ray parenchyma cells than in ray tracheids.

Rows of ray tracheids are generally interrupted by a parenchyma cell at the border of annual rings in spruce, and this interruption can affect the treatability of the wood (Liese and Bauch, 1967; Baines and Saur, 1985; Baines, 1986).

Hayashi and Kishima (1965) reported greater radial flow in Japanese pine due to high permeability of ray tracheids and ray parenchyma and further observed flow from ray tissues to the longitudinal tracheids in latewood. In contrast to findings of above authors on radial flow, Bailey and Preston (1970) showed that semi-bordered pits between ray parenchyma and axial tracheid, and bordered pits in ray tracheid usually encrusted, and also ray parenchyma is impermeable to water-borne preservatives in Douglas-fir sapwood.

If these flow paths are neglected, a very simple flow model for softwoods results, in which fluids flow from tracheid to tracheid through the bordered pit pairs. This is in general agreement with microscopic observations (Wardrop and Davies, 1961; Behr *et al.*, 1969; Bailey and Preston, 1969). In this case, the individual ray cells bordering the horizontal resin canal are arranged heterogeneously. Communication between the wood rays and the tracheids occurs through either half-bordered pits having the typical tapering pit chamber on the tracheid side and a straight bore chamber on the ray cell side, or simple pits with straight bores on both sides. These pits lack the thickened central torus common to full bordered pits.

2.8.4 Flow in Heartwood and Sapwood

Preservative treatment of spruce heartwood is a problem because of its non-durable classification and need for treatment to get a long service life. Spruce sapwood is known to be several times more permeable than heartwood (Krahmer and Cote, 1963; Erickson, 1970), e.g. the sapwood in Norway spruce (*Picea abies*) proved more treatable (Smith, 1986). The primary causes of heartwood and sapwood permeability differences are due to differences in aspiration, and to the amounts and character of the extractives, especially in the heartwood in cases of liquid flow (Erickson, 1970). Extractives in wood tend to reduce permeability, especially in heartwood (Krahmer and Cote, 1963; Erickson, 1970), and can have a significant effect on the treating results (Nicholas, 1982; Baines and Saur, 1985). It is generally agreed that the deposition of extractives in the heartwood of spruce does not confirm appreciable durability (Krahmer and Cote, 1963; Erickson, 1970).

In addition to the general differences between heartwood and sapwood, other anatomical and site influences have been noted to affect treatability. Permeable, treatable spruce (*Picea* spp.) and Douglas-fir (*Pseudotsuga menzeisii*) specimens are known to have longer tracheids (Liese and Bauch, 1967; Baines, 1986), and to have larger lumina (Fleischer, 1950). The difference in fiber length has been documented to be as high as 27 % (Liese and Bauch, 1967). Several studies have found variations in the permeability of Norway spruce (*Picea abies*) from different growth sites (Baines and Saur, 1985; Peyresaubes, 1985). Another study confirms the site influence on the longitudinal treatability of Norway spruce (*Picea abies*) but reported it to be of minor importance because it was not seen to affect flow in the radial or tangential directions (Liese and Bauch, 1967).

2.8.5 Flow in Earlywood and Latewood

As with most discussion of the characteristics of spruce, the differences in permeability and fluid flow through earlywood and latewood are also in debate. In green wood, earlywood is more permeable than latewood whilst latewood is more permeable than earlywood in seasoned material (Petty and Preston, 1969). One study found the lateral movement of preservative in white spruce (*Picea glauca*) to be the same in earlywood and latewood (Keith and Chauret, 1988). Other authors cite more random variability, where sometimes the earlywood from an annual ring is more permeable than the latewood, and sometimes vice versa (Baines and Saur, 1985; Baines, 1986).

Liquid flow in wood occurs as mass transport or movement in the cell lumina but is affected by the slower passage of liquids through the pits in adjacent cell walls and across the permeable cell wall between adjacent cells. The liquid transport from one tracheid to another takes place through the bordered pits. There are smaller and fewer pits in latewood tracheids than in earlywood and generally fewer pits of smaller size on the tangential surfaces of all longitudinal tracheids; thus, most of the fluid flow between tracheids takes places in the tangential direction if flow through the rays is not considered (Siau, 1984). The number of pits per tracheid varies from 50 to 300 in earlywood, with only 10 to 50 rather small bordered pits in latewood (Stamm, 1964). The length of ray tracheids in latewood is also about half that of the earlywood cells and is one explanation of why preservative penetration in green spruce (*Picea* spp.) is often better in the earlywood than in the latewood (Liese and Bauch, 1967; Baines, 1986). Phillips (1933) showed that pit aspiration due to drying reduced earlywood flow. In spruce the degree of pit aspiration as in the region of 97 % while in Scots pine (which is known as a permeable species) it was in the region of 93 per cent. It is unlikely that this totally accounts for the differences in permeability of these two species.

The thicker strands and tighter margo texture in latewood pits, their smaller diameter, and the configuration of the pit chamber contribute to their stiffness and resistance to aspiration (Liese and Bauch, 1966; Comstock and Cote, 1968; Petty, 1970). From observation of dye through the thin sections it seems that the flow was confined to the last-formed earlywood region in which the pits are larger in latewood and have larger gaps between the radial strands in the membranes (Petty, 1970).

Bailey and Preston (1970) used a pressure of 45 lb/in2 (3 bar) for 30 minutes and noted longitudinal penetration greater in latewood than earlywood in dried Douglas fir; all tracheids showed some sign of penetration.

2.9 Comstock Model for Softwood Permeability

The flow of fluids through softwoods is essentially through the tracheids which are interconnected by bordered pit pairs. The pit openings are very small in diameter compared with the lumens and are therefore assumed to provide all the flow resistance. Therefore it is the number and condition of the pit openings which determines the permeability. The model proposed by Comstock (1970) further assumes that all the pits are on the radial surfaces at the tapered ends, as illustrated in Figure 2.6. All pit openings are assumed equal in size. Figure 2.6 shows four pit pairs open to each tracheid which are shared by two tracheids resulting in two pit pairs per tracheid. It is evident that both longitudinal and tangential permeabilities are increased by the relative number of bordered pit pairs in parallel per unit cross-sectional area perpendicular to the flow direction and are decreased by the number in series per unit length in the flow direction.

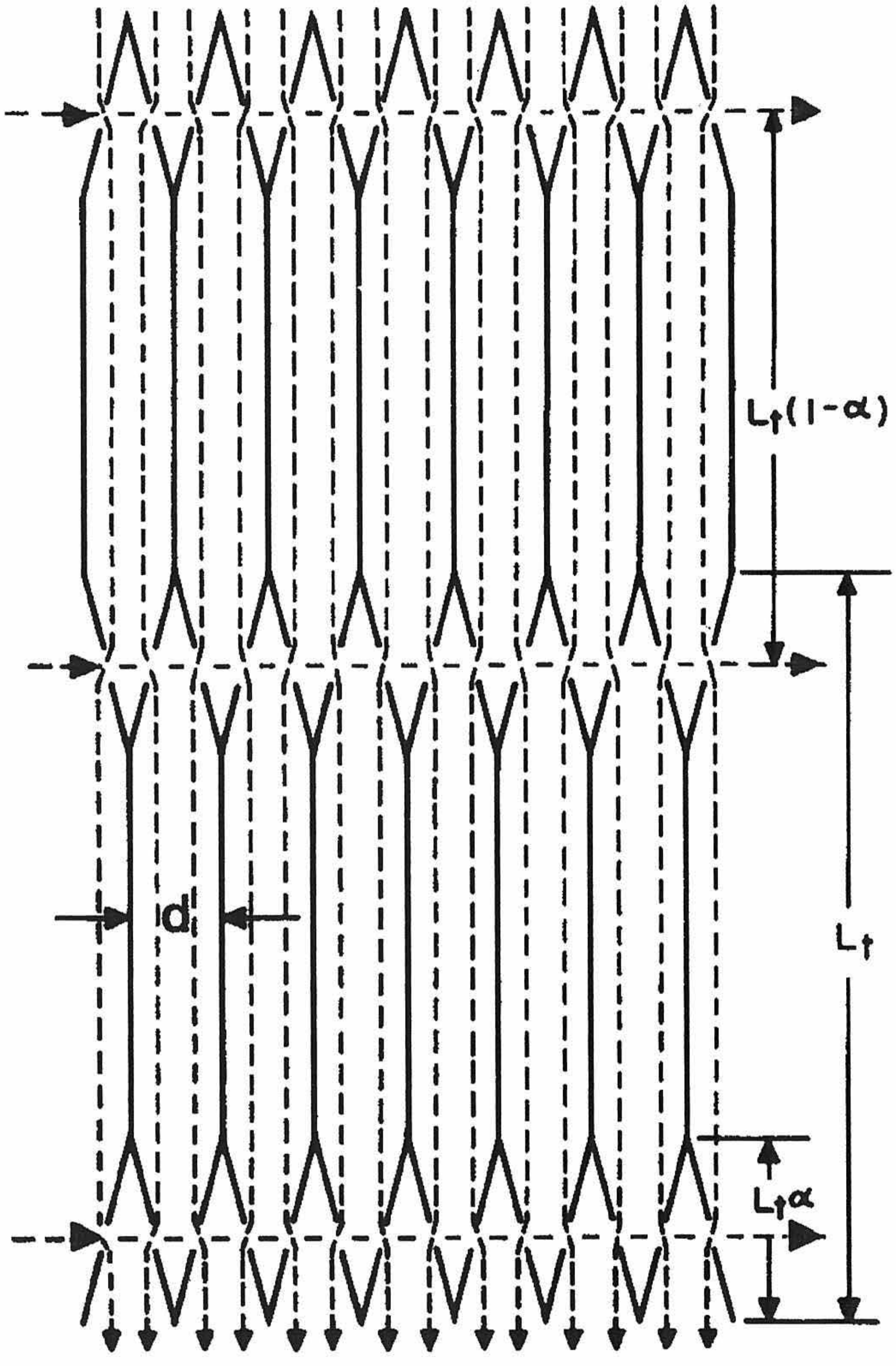


Figure 2.6. Softwood flow model according to Comstock (1970). Tangential section showing pits on the radial surfaces of the tapered ends of the tracheids (from Siau, 1984).

In order to derive the ratio of longitudinal to transverse (tangential) permeabilities, it is only necessary to set up proportions for both the longitudinal and tangential values.

In the longitudinal direction there are two parallel paths per tracheid, or $2 / (2\ r_t)^2$ or $1 / (2\ r^2_t)$ per cm^2 of cross-sectional area, where r_t = radius of tracheid. The number of pit openings traversed per cm of lengths is $1 / [L_t\ (1 - I)]$, where L_t = length of tracheid and I = fraction of overlap. Then,

$$k_L \sim (1 / 2\ r^2_t) / [1 / L_t (1 - I)] = L_t (1 - I) / 2\ r^2_t \qquad (2.3)$$

where k_L = longitudinal intercept permeability, cm^3 (liquid)/(cm atm s).

In the tangential direction there is one parallel path per tracheid, or $1 / [2\ r_t\ L_t\ (1 - I)]$ per cm^2 of area. The number of pit openings traversed per cm of length is $1 / r_t$. Then,

$$k_T \sim 1 / [2\ L_t\ (1 - I)] \qquad (2.4)$$

where k_T = tangential intercept permeability, cm^3 (liquid)/(cm atm s).

Therefore,

$$k_L / k_t = L^2_t\ (1 - I)^2 / r^2_t \qquad (2.5)$$

Assuming a length to diameter ratio of 100 for the tracheids $L_t / r_t = 200$ and equation 2.5 may be simplified to:

$$k_L / k_t = 40000\ (1 - I)^2 \qquad (2.6)$$

Equation 2.6 reveals that the ratio k_L / k_t can vary between 10000 and 40000 as I decreases from the maximum value of 0.5 to zero. This is in reasonable agreement with experimental results (Comstock, 1970).

2.10 Methods Used in Determining Permeability

The simplest technique for comparing the permeability of two or more samples of wood is to submerge the samples in a liquid and remove them after a set time, weigh them and compare liquid uptake as either an absolute quantity or in relation to the weight or volume of the samples. If the solution is coloured some information on the depth of penetration can be obtained also from this. The method is suitable for dry wood only, but in the context of work aimed at finding information relevant to vacuum/pressure treatment this limitation is quite acceptable. By sealing all but one of the faces of the wood sample it is simple to limit penetration to one grain direction and this was the method used by Hayashi *et al.* (1967).

These workers further refined the technique by attaching the wood sample to a weighted platform and suspending this from a direct reading balance. With this apparatus they were able to plot uptake as mg. liquid per cm^2 of surface area against time. The disadvantage of this technique is that uptake can be measured only at normal atmospheric pressure and the blocks are filled with air which must be displaced out during liquid uptake.

Graham (1964) used a simple "sink-float" test to compare the permeability of Douglas-fir samples. Small specimens of dry wood (e.g. 3/4 inch cubes or samples made longer in the axial direction) were evacuated in a vacuum desiccator and then liquid was admitted while the samples are still under vacuum. A perforated plate was used to prevent the samples rising to the surface and they were held (floating) against the underside of this. Air is then admitted to the jar and the time taken for individual samples to sink is noted. This uptake will not represent total saturation of the wood because of the higher density of wood substances but if the basic density (oven dry weight/swollen volume), and initial weight and moisture content are known, the actual uptake can be calculated. For most wood species the sinking point in water will correspond to an uptake of 75-85 % of the maximum possible uptake. Unidirectional penetration can be obtained in this method also by sealing all but one (or two) of the faces. This technique is an improvement on that used by Hayashi *et al.* (1967) in that by using an initial vacuum to remove the air in the wood, the conditions come nearer to those pertaining in pressure treatment. Although it would not be possible to increase the pressure above atmospheric pressure in a vacuum desiccator it would be a relatively simple matter to construct a chamber (with a siting window, or wholly from perspex) so that positive air pressures could be exerted after the vacuum was released, and noting the "sink time" of individual samples when subjected to various pressures. The disadvantage of this technique is that, even with refinements of pressure, there is only one uptake/time observation possible i.e. when the sample just commences to sink.

Koran (1964) used 3/4 inch cubes (of Douglas fir) sealed on five sides with several coats of a solution of cellulose acetate in acetone to determine unidirectional uptake of creosote under various pressures and at various temperatures. No mention was made of an initial vacuum so presumably this was not used; creosote is often applied by the Lowry or Rueping process where the liquid is injected against atmospheric or raised air pressure in the wood in order to recover surplus oil at the completion of the treatment. No siting or uptake monitoring devices were used and treatment was finished after a pre-determined time (8 hours) where upon the blocks were removed, weighed, and the uptakes calculated as a percentage of the uptake in those blocks which were considered to be saturated. The obvious disadvantage of this method is that there is no means of judging how the penetration is proceeding during treatment, and numerous experimental runs must be made for every size and species to determine an optimum time for each set of conditions.

A completely different approach has been to determine the permeability of wood by measuring the flow rate of liquid or gas through wood specimens. The simplest of these utilizes a hydrostatic head of water with the wood sample fixed in a tube leading from the bottom of this reservoir. Water emerging from the other end of the sample is collected in a graduated vessel and volumes collected are plotted against time. These volumes can be expressed in absolute terms for standard sized specimens or related to the length and cross-sectional area of the specimen. Hayashi *et al.* (1966) increased the pressure differential across the specimen by connecting the outflow end to a vacuum pump; a desirable consequence of this modification was that the sealing sheath was forced more tightly around the specimen. They measured "permeation rates" as cc/cm^2 against time. Hartmann-Dick (1954) used a higher pressure differential of two atmospheres applied to a Thiessen bacterial pressure filtering apparatus in which the porcelain filters were replaced with discs of wood. He obtained "filtration values" for various wood samples using an equation

$$FV = (L \times dw) / (A \times t) \qquad (2.9)$$

where FV = filtration value, L = liquid (ml), dw = disc width (mm.), A = sectional area (cm^2), t = time (min).

Bailey (1966) used regulated water mains pressure and compressed nitrogen to force water through round discs of Douglas fir clamped into a metal holder with O-rings. He also used a back pressure (compressed nitrogen) to vary the differential in relation to the applied pressure. The wood discs were all made to a standard size and flow rates were measured as ml/min and plotted against time. The same apparatus was used by Petty (1967) but in this case the main object of the investigation was to calculate pore sizes in bordered pit membranes using non-swelling liquids and gases.

Choong *et al.* (1966) used gas flow through thin sections of dry wood to calculate the permeability of six softwoods and nine hardwoods. In their apparatus the wood sections were cemented to the end of a cylindrical glass tube and all the exposed wood except the area corresponding to the orifice of the tube was coated with paraffin wax. The pressure differential was obtained by a vacuum on the exit side of the specimen and flow rates were measured by the rate of rise of liquid in an inverted graduated cylinder (in an open liquid tank) on the entry side. Measurements could only be made until the air initially present between the liquid and the specimen was exhausted.

Smith and Banks (1970) used gas flow through wood specimens to determine permeability and pore and pore size and were able to separate the viscous (Poiseuille) component of the total flow from the slip (Knudsen) flow of the gas molecules. They used hydrogen, nitrogen, helium, neon, and krypton, and checked the pore sizes obtained by using artificial pore-sized constrictions made by sandwiching various micropored filters between sections of finely pored diffuse-porous hardwoods.

Although the results from these flow rate investigations provide a general measure of the permeability of the wood specimens used, and there is some agreement between the permeabilities obtained and the known treatability characteristics of the species, the approach has several serious disadvantages. Where gases are used to measure flow rates the moisture content of the wood will alter with time until it reaches equilibrium with the system and this will depend on the relative humidity and temperature of the gas. Progressive changes will alter the flow rates and the only practical way to avoid this is to use oven dry wood, a condition that is never encountered in normal wood preservation. Smith and Banks (1970) state that liquid flow can be predicted from these (gas flow) data with some qualifications; 1) Liquid pressure may cause pit sealing with some species, 2) Swelling liquids may alter the characteristics of the medium (e.g. wood).

A very real problem with flow rate measurements is the difficulty of effectively sealing the wood specimens so that the flow is restricted to one grain direction and short circuiting is prevented. In this respect the systems used by Hayashi *et al.* (1966) and Choong *et al.* (1966) are the most effective in that external pressures tend to reinforce the seal by pressing it tightly against the surfaces of the wood. Where pressure is exerted against the seal it seems almost impossible to prevent some short circuiting by the liquid. When sections of very refractory wood were prepared for radial and tangential penetration in the apparatus designed by Bailey (1966), the use of dyed solutions showed that movement often took place around the O-rings instead of directly across the specimen.

Perhaps the greatest criticism of flow rate measurements is that once a flow path has been established liquid will continue to move through this (unless it becomes blocked by pressure on pits, particles in the solution, or air embolisms) and large areas of the wood may remain unpenetrated. If any artificial openings, (e.g. checks or splits caused by drying or specimen preparation) exist, the readings will be abnormally high and this will also be the case with species that have large unobstructed resin canals running in the same direction as the liquid movement. Even where resin canals or artefacts do not exist the flow may not be uniform over the whole area of the specimen; Petty (1967) (using dyed styrene which was later polymerised in the cells) showed that even in green wood having a minimum number of aspirated pits, longitudinal flow was not uniform and a considerable number of the tracheids appeared to be non-conducting. In air dry spruce wood, where the majority of the earlywood bordered pits were aspirated, longitudinal penetration of the reduced basic fuchsin solution was almost wholly through the latewood tracheids and even in this region not all of the cells were conducting (Petty, 1970).

For these reasons, permeability as determined by flow rate measurements may not bear a very close relationship to treatability with preservative solutions such as copper-chrome-arsenate (CCA) where uniform and even penetration to a condition of virtual saturation of the wood is essential.

2.11 Collection and Preparation of Experimental Samples

Studies of anatomical and physical characteristics of wood are normally made on representative samples, (usually cross-sectional discs) cut at proportional heights in the tree. In timber improvement studies, however, it is necessary to retain the tree as a source of potential breeding material and a wood assessment must be made on a sample taken by a non-destructive technique. Specimens must be small and few in number if permanent injury to the tree is to be avoided, and a convenient technique is to sample from bark to pith using a large increment borer to give a cylindrical core or boring, approximately 15 mm in diameter. Sampling is at breast height, as a matter of convenience, and at fixed cardinal points in each tree. With the development of techniques for holding and aligning the borer (Wheeler, 1964) and maintaining it in a sharp condition (Goodchild, 1963), cleanly cut, unbroken, straight borings are obtained.

At relatively high average moisture contents, the moisture content in the outer millimetres (of Norway spruce, *Picea abies*) can be much lower, and the more or less completely aspirated pits close to the surface prevent penetration (Johansson and Nordman-Edberg, 1987). On logs felled during seasons of botanic activity penetration of preservative is poor (Dahlgren, 1985). Therefore, the type of timber for impregnation is mostly seasoned timber dried to values around or below fibre saturation point (FSP). Precise specifications vary for different preservative systems e.g. CCA is 28% or less. This is done to reduce the free water in the cell lumens and to leave voids for the bulk flow of the preservatives. Wilkinson (1979) stated that for wood preservatives to penetrate deeply, logs have to be debarked, cut to sizes appropriate to end uses and seasoned or dried. Additionally, surfaces must be free from saw dust, paint or other surface coating.

2.12 Preservative Treatment in Relation to Permeability

The structure of wood differs between and within a species has a great effect on preservative treatment. This affects the uptake despite the pressure being applied, although some refractory species cannot be treated even under maximum applied pressure. The difficulty of obtaining satisfactory treatment of some species of wood a problem facing the timber preservation industry (Petty, 1970b) e.g. Sitka spruce is regarded as untreatable by conventional pressure methods (Liese and Bauch, 1967). This is especially the case with natural rounds (i.e. piles, telegraph and electricity transmission poles and fence posts).

Experience has shown that normal vacuum/pressure impregnation with CCA solutions for treatment of Sitka spruce does not always achieve uniform and even penetration, particularly in natural rounds where a deep envelope of well treated wood is essential.

2.12.1 Variations of Permeability between Wood Species

Permeability is an extremely variable property of wood. Smith and Lee (1958) measured the ratio of longitudinal to tangential air permeability of approximately 100 species and found a range of values with a ratio of $5x10^6$:1 for hardwoods and $5x10^5$:1 for softwoods.

As is shown in Table 2.1, the red oaks may have permeabilities as high as 100 darcys because of their large earlywood vessels. American basswood (*Tilia americana*) is also very permeable because of its open, diffuse-porous structure. Pine sapwoods are among the most permeable softwoods and may have values as high as 1 to 8 darcy. However, the spruces and cedars are usually much lower, in the 10^{-1} darcy range. One of the lowest is Rocky Mountain (intermountain) Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) heartwood in the range of 10^{-3} darcy, making it extremely refractory to impregnation.

Table 2.1. Approximate values for some common classifications of wood (Siau, 1984).

Longitudinal permeability (darcy)		Species
100	10^2	red oak (radius = 150 μm)
10	10^1	basswood (radius = 20 μm)
1	10^0	maple, pine (s), Douglas-fir (s)
0.1	10^{-1}	spruces (s), cedars (s)
0.01	10^{-2}	Douglas-fir (h) (Pacific coast), white oak (h), beach (h), cedar (h)
0.001	10^{-3}	Douglas-fir (h) (intermountain)
Transverse permeability (darcy)		**Species**
0.0001	10^{-4}	the species are in approximately the same order as those for longitudinal permeabilities.
0.00001	10^{-5}	
0.000001	10^{-6}	

s = sapwood, h = heartwood

Comstock (1970) summarized ratios of longitudinal to tangential permeabilities of softwoods between 500:1 and 80000:1 with most of these above 10000:1 in reasonable agreement with his model. On the other hand, longitudinal to radial ratios extended from 15:1 to 50000:1. This greater variability in the radial direction could be related to large differences in the permeability of ray tissues.

2.13 Pressure Application Processes

2.13.1 Full-Cell Process

The full-cell process is one of the most successful and widely used techniques of pressure processing for the treatment of wood; as the name implies, the wood cells are filled with liquid under pressure in the treatable zone. It was invented by the engineer, John Bethell, in 1838 and was initially used for injecting oil into wood. For many years it was called the Bethell process with coal tar creosote, and the Burnett process or Burnettizing with zinc chloride solution (Hunt and Garratt, 1967). It is now also known as the vacuum/pressure method and is almost invariably used in impregnating wood with water-borne preservatives or creosote. The object of the full-cell process is to fill the cells of wood to capacity. This results in the maximum amount of preservative being retained by the wood (Nicholas, 1973). This is achieved by applying an initial vacuum to the wood before filling with preservative, and then applying pressure (BRED, 1977). When creosote is used, it is heated between 65-100°C during the pressure period to reduce viscosity and improve penetration, although water-borne preservatives do not need heating (Wilkinson, 1979).

Numerous authors (Hunt and Garratt, 1967; Purslow, 1974; Richardson, 1978; Wilkinson, 1979; Findlay, 1985; TRADA, 1986; Eaton and Hale, 1993) describe the stages of the full cell process. The dried wood is loaded into a stout steel cylinder and sealed with a pressure resistant door. Initial vacuum is then created in which the air is pulled out from wood cells making easier to impregnate with preservative. The vacuum gauge reading in most treatment is -0.75 or -0.84 bars (635 mmHg) held between 15 minutes to 1 hour depending upon the commodity treated. Thirdly, whilst maintaining the above vacuum, preservatives are flooded into the cylinder. Vacuum is released and then positive pressures of 10 - 14 bars are applied to fill the wood cells throughout the wood with preservative and held for 1 - 6 hours for creosote or 12.4 - 14 bars and held for 30 - 180 minutes for CCA. Pressures are gradually raised to $1.03 - 1.38 \times 10^6$ N/m^2 (150 - 200 lb/in^2, 10 - 13.3 bar) and maintained for specific time or until the required amount of preservative is forced deeply into the wood. When pressure is released 5 - 15 % of preservative is forced out of timber into the cylinder due to expansion of the small amount of air compressed within the wood cells; this is known as 'kick-back' (Wilkinson, 1979). The pressure is normally applied by a hydraulic pump although some small scale laboratory plants employ gas pressure (Eaton and Hale, 1993). Finally, the excess preservative is drawn back to a work/storage tank and a final vacuum of -0.84 bar is reached. With CCA this is immediately released. This lessens the dripping which would otherwise occur when treated timber is unloaded from the cylinder. Only a slight amount of preservative is retrieved from the wood cells and a maximum amount of preservative is retained in the wood (Wilkinson, 1979).

2.13.2 Empty-Cell and Other Related Processes

The other common process is called the "empty cell process." In this process, the wood is impregnated with preservative under high pressure on top of air trapped within the wood. The trapped air is later allowed to expand, ejecting preservative from the porous spaces but leaving the cell walls impregnated or coated with preservative (Richardson, 1993). This method reduces bleeding of the treated timber in service.

Empty cell process are of two types: the Rueping and the Lowry processes. The Rueping process was patented by Wassermann in 1902 (Germany) and is commenced by applying an initial air pressure; when the entire process is completed the pressure is released. The compressed air in the cells drives out some of the preservative and a short period of vacuum recovers more preservative so that the net retention in the wood is only about 40 % of gross absorption and a saving of 60 %. On the other hand, the Lowry process, patented in 1906, differs in that it relies on compression of air at atmospheric pressure for return of excess preservative so that there is no initial compression stage. The recovery of preservative is about 40 % (Richardson, 1978; 1993).

Empty cell processes have been modified into variety of processes known today, for instance: the MSU process, developed at Mississippi State University (Kelso, 1977), and the Pulsation process (Hosli, 1980; Hosli and Filion, 1983) which was developed to increase creosote penetration in the refractory red heart of beech and has been investigated for spruce treatment in Canada (Hosli and Ruddick, 1988). Other processes like the Oscillating Pressure Method (OPM) (Henriksson, 1954; 1958; Hudson and Henriksson, 1956) and the

Alternating Pressure Method (APM) (Bergervoet, 1984), based on the Lowry process, are applications where pressure is applied rapidly and fluctuatingly. Comprehensive information regarding the variety of pressure processes is reviewed elsewhere (Hunt and Garratt, 1967; Richardson, 1978; Wilkinson, 1979; Findlay, 1985; Eaton and Hale, 1993).

Despite differences in design and technology, or the full cell or empty cell processes, the general principle of operation is basically the same. However, a different amount of pressure is applied depending on the type of preservative, type of commodity to treat and its ease of penetration (permeability) and the end use of certain hazard situation. Therefore, the amount of pressure application has tremendous effect on penetration and retention of preservative used in the wood.

2.14 Preservative (CCA Salt) Retention

The retention (amount of preservative retained after treatment) is the important factor influencing the effectiveness of preservative systems in extending the service life of wood. The retention in treated wood is influenced by permeability and surface to volume ratio (Arsenault, 1973).

Permeability is a more significant factor determining retention than either pressure or reciprocal viscosity. The most permeable areas will fill first to a high retention followed by subsequent filling of the lower permeability regions (Siau, 1970a).

In this thesis, retentions have not been used to give a product of uptake and solution. Instead estimates of void volume and the percentage of void volume filled have been used as recommended by Siau (1984).

3 MATERIAL AND METHODS

This chapter provides information on the seed origins and the sites where they were growing, and explains the procedures followed for data assembly and processing.

3.1 The Seed Origins Sampled and Trial Sites

The study was carried out on 80 twenty year old trees from eight seed origins (Table 3.1a) of Sitka spruce grown at two experimental sites; Rhondda in South Wales and Dalby in North-East England. All the trees were growing in a IUFRO (International Union of Forest Research Organisation) seed origin trial planted in 1975. Eight seed origins from throughout the whole distribution of the species from north to south were chosen for this study. The two sites represent extremes of the range of sites on which this species is used in Britain, and were chosen for this reason.

The geographical locations of the selected seed origins and the general characteristics of the trial sites are presented in Tables 3.1 and 3.2 respectively. A map of the natural distribution of Sitka spruce is shown in Figure 3.1, which also includes a map of the United Kingdom with the site locations.

Table 3.1a. Geographical locations of the seed origins (arranged north to south along the natural distribution of Sitka spruce).

Region	Seed Origin	Latitude (N)	Longitude (W)	Elevation (m)
Alaska	Duck Creek, Juneau Area	58° 37`	134° 58`	30
British Colombia	Inverness, Prince Rupert	54° 20`	130° 25`	0 - 30
Queen Charlotte Islands	Masset (Commercial Seedlot)	54° 00`	132° 00`	0 - 15
North Washington	Forks, Olympic Rain Forest	48° 07`	124° 30`	120 - 140
South Washington	Raymond, Willapa Bay	46° 68`	123° 87`	15 - 30
North Oregon	Necanicum	45° 82`	123° 77`	45
South Oregon	Brookings, Oregon	42° 25`	124° 38`	90
California	Crescent City, California	41° 67`	124° 18`	10 - 15

Table 3.1b. Identification numbers of the selected seed origins.

Region	MRN	IUFRO (no)	FC (no)
Alaska	3	3024	70 (7987) 101
British Colombia	20	3044	70 (7112) 103
Queen Charlotte Islands	37	7111	70 (7111) Lot2
North Washington	53	3003	68 (7971) 100
South Washington	59	3009	68 (7972) 102
North Oregon	62	3012	68 (7951) 101
South Oregon	68	3018	68 (7952) 102
California	70	3020	69 (7947) 101

MRN = map reference number used in Figure 3.1., FC = Forestry Commission seed identification number. IUFRO = International Union of Forest Research Organisation seed identification number.

Table 3.2. General characteristics of trial sites at Rhondda (Wales) and Dalby (England).

Characteristic	Rhondda	Dalby
Year of establishment	1975	1975
NGR (National Grid Reference)	SN940019	SE882849
Elevation (m)	450	183
Rainfall (mm/year)	2400	835
Exposure	Severe	Severe
Lithology (geology)	Carboniferous sandstone	Soft limestone
Soil type	*Molinia/Calluna* bog	Ironpan
Forest site type (previous use)	Uncultivated hill pasture land	Open moorland
Site preparation (cultivation)	Single furrow tine ploughing	Complete ploughing
Fertilisers	375 kg/ha Gafsa	375 kg/ha Gafsa
Spacing (planting)	2 x 2 m	2 x 2 m
Design	Randomised blocks	Randomised blocks
Replication	2	4
Plot size	Square plot 3 x 3 (9) tree - STS	Square plot 3 x 3 (9) tree - STS
Seed origins	34	64
Dominant ground vegetation	*Juncus* spp., *Molinia caerulea*	*Rubus* spp., *Rosa* spp., *Deschampsia flexuosa*

- The trial sites Rhondda and Dalby are indicated as R and D respectively in Figure 3.1
- STS = short thinning section

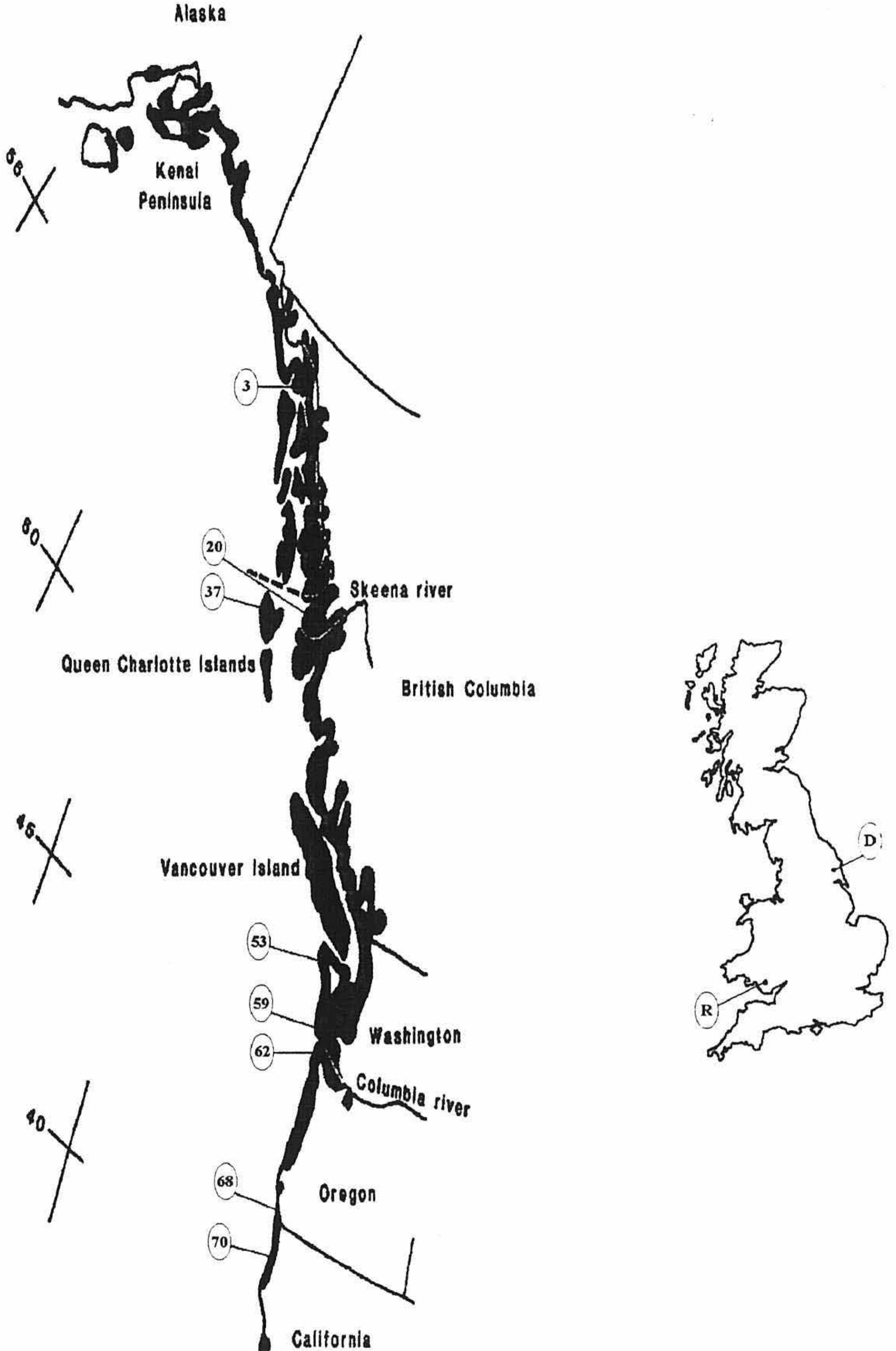


Figure 3.1. (a) Natural distribution of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) with locations of selected seed origins, (b) Locations of trial sites in Great Britain.

3.2 Selection of Sample Trees

Following an appraisal of the site, five trees of each of the eight seed origins (a total of 40 trees from each site) were selected for good butt form, circular cross-section, uniform crown development, freedom from root influence extending up the tree, and freedom from sweep and drought cracks, in anticipation of their yielding timber of normal growth at breast height. Trees of average diameter for each seed origin were chosen and any trees with obvious double leaders, uneven crowns or other major irregularities in the stem were rejected.

The selected trees were felled in January and February 1995 at 0.5 m above ground level and the 3 m log above this was marked to assist in identification. The 40 trees from Rhondda were transported to Bangor on 16th January 1995, and those from Dalby on 28th February 1995.

3.2.1 Field Data

After felling and prior to conversion, the mean diameter at breast height[1] (dbh) was measured. The stem diameter was also measured and recorded at the base, centre and top of the trees to enable later calculation of tree volume. The trees were labelled with their dimensions. Individual tree parameters measured immediately after felling are recorded in Appendix 1.

3.3 Selection of Sample Discs

Three discs 5 cm thick were cut from each tree for the determinations of density, preservative penetration and uptake, and anatomical structure. The discs were taken 1.3, 2.3 and 3.3 m above ground level. Each disc was marked with a code which identified site, seed origin, tree number and position in the tree. Measurements were made of the diameters of the selected discs and the widths of their sapwood zones.

---

[1] 1.3 m above ground level (Philip, 1994).

3.4 Collection and Preparation of Experimental Samples

The selected trees were sampled by means of a 15 mm plug as follows; the transverse face of each disc was divided into 4 sections (Figure 3.2), and four cylindrical samples of 15 mm in diameter and 50 mm in length were produced radially (in east-west and north-south directions) and longitudinally (in the stem direction) from each disc using a core forming drill at an internodal position of 1.3 m, 2.3 m and 3.3 m heights of the trees. Each core was then labelled (Section 3.3) with the addition of a sample number, and was then kiln dried to 12 per cent moisture content.

From the one end of each longitudinal core, thin samples 3 mm thick were cut and labelled with the original core code. The remainder of each longitudinal core was then cut to 30 mm in length. Thereafter, the three small samples (3x15 mm diameter), referred to as "density samples", were taken to be used for density determinations (Section 3.6). The three core plug samples (30x15 mm diameter), referred to as "treatment samples", were used in the treatment experiment (Section 3.7). The remaining 4th sample was used for anatomical analyses (Chapter 6).

3.5 Determination of Growth Ring Width Characteristics

The radial width of the density samples was measured with a micrometer and the number of growth rings on its transverse surface were counted manually using a x10 lens. Mean growth ring width was then calculated by the following equation:

$$g = r / n \qquad (3.1)$$

where, g = mean growth ring width (mm); r = radial width (mm); n = number of growth rings (Personal Communication from Ms. D. Aebischer, 1995).

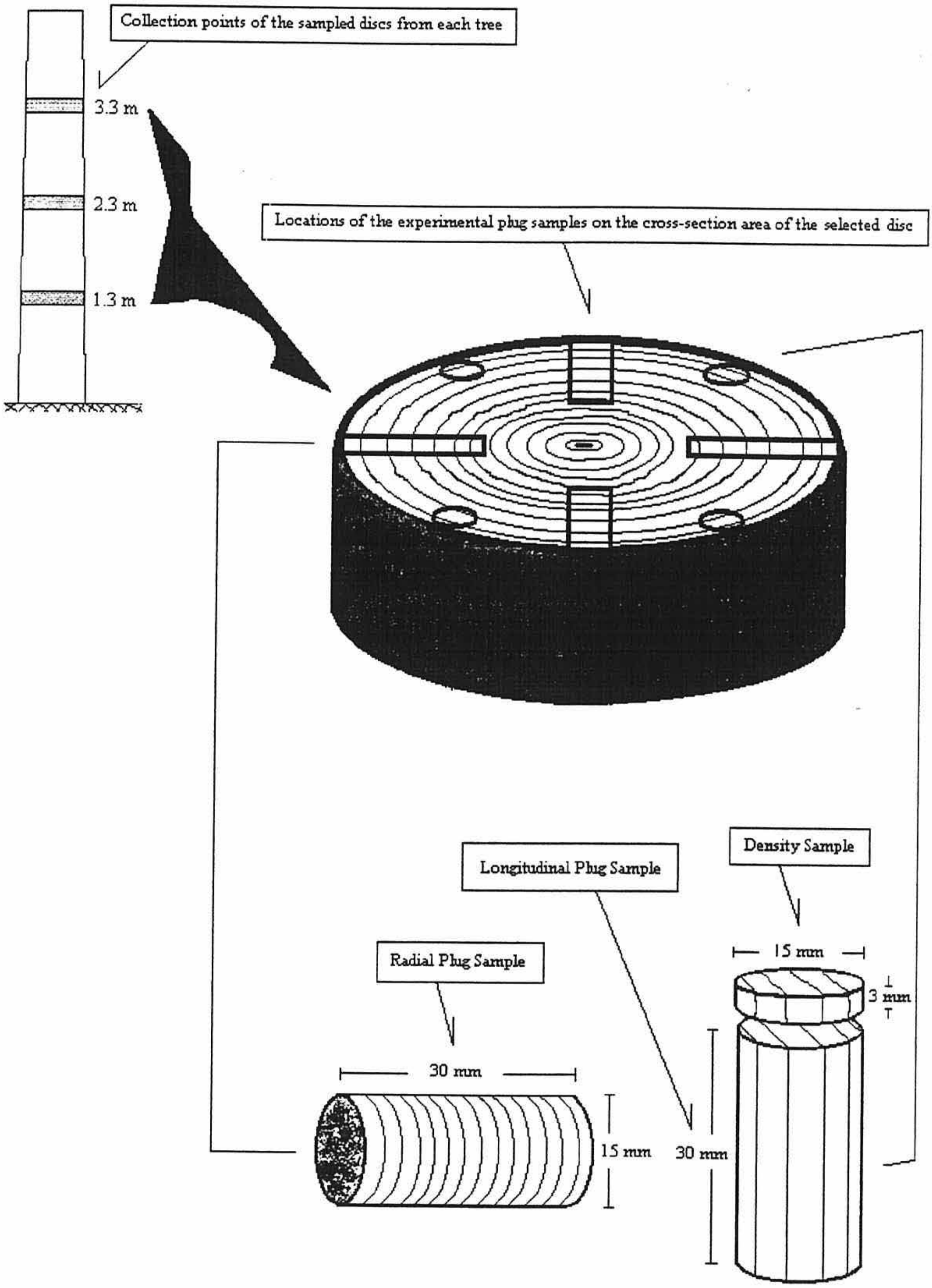


Figure 3.2. The initial locations of the experimental plug samples on the transverse section of the selected discs.

3.6 Determination of Density

The maximum moisture content method was used to determine the density (Equation 3.2). The weight after drying until constant weight (at 103±2°C) divided by the green volume (measured by the water displacement method, Oleson, 1971) gives the density. To obtain the green volume experimental samples were firstly saturated with distilled water by pulling a vacuum and soaking for 10 days. The volume of a body is then determined most accurately by determining the amount of liquid which it displaces. After having performed this procedure, the density of the experimental samples was calculated from the following equation:

$$d = [Mo / (Mo / G) + (Ms - Mo)] * 1000 \qquad (3.2)$$

where d is the density of wood sample (kgm^{-3}), Mo the oven dry weight of sample (g), Ms the weight of sample saturated with deionised water (g), G the specific gravity of cell wall substance (taken to be 1.53 g cm^{-3}) and 1000 the constant for converting the result into kilograms per cubic meter (Kollman and Cote, 1968; Bamber and Burley, 1983; Simpson, 1993).

The density samples (3x15 mm diameter) were only taken from longitudinal plug samples because those from radial plugs gave a lower number of growth rings. The number of growth rings for longitudinal density samples (LDS) and radial density samples was 4 - 7 and 1 - 3 respectively. In addition, the LDS are shorter in the tracheid longitudinal axis (fibre direction) and are thus easier to saturate by water.

In a trial experiment on density determination, it was shown that shorter samples with fewer tracheids were fully saturated.

The horizontal variation of the density values (from pith to bark) refer to the outer growth rings only, which is the actual cross-section area of the experimental samples used in this study. The vertical variation (from base to top of the tree) was plotted for each growth sheath against the sampled disc locations from base upward in the stem.

3.6.1 Determination of Green Volume

Loose fibres were removed with a razor blade, and to obtain the actual volume and mass, each experimental sample was measured with a micrometer and weighed. As shown in Figure 3.3, the samples (1) were then placed into a vacuum desiccator (2), held down 20 mm below deionised water (3) with a wire gauze (4). 25 ml of fungicide was added to the water. After the application of vacuum of -80 kPa (600 mmHg) for 12 hours, the desiccator were kept closed for 12 hours.

This vacuum impregnation procedure was continuously performed for 10 days. After having finished the soaking time under vacuum condition, the experimental samples were assumed to be fully saturated by water.

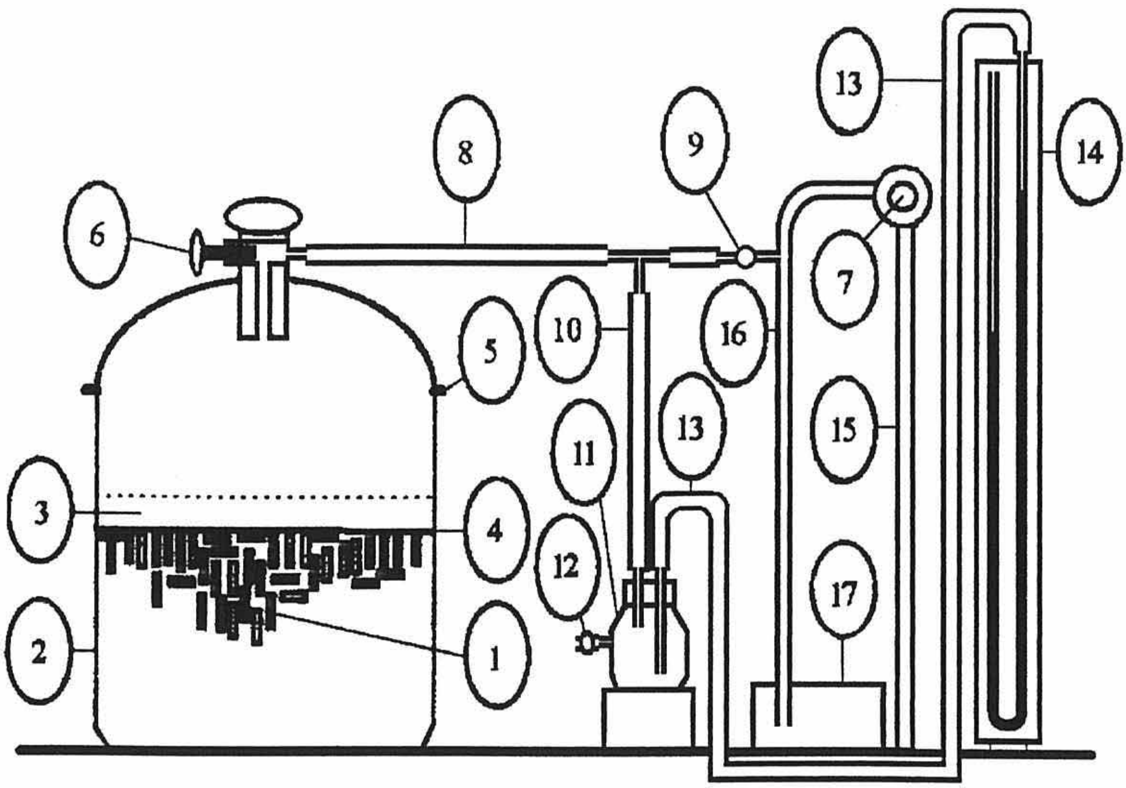


Figure 3.3. A diagram showing the vacuum apparatus for saturating the samples with deionised water: 1, experimental blocks; 2, vacuum desiccator; 3, deionised water; 4, wire gauze; 5, lid of the desiccator; 6, valve of the desiccator; 7, tap for water fall; 8, rubber tubing for desiccator; 9, vacuum valve; 10, rubber tubing for vacuum trap; 11, vacuum trap; 12, adjusting valve for required vacuum level; 13, rubber tubing for mercury manometer; 14, mercury manometer; 15, incoming water; 16, outgoing water; 17, sink.

The samples were then individually weighed in a beaker of deionised water to determine the green volume as follows (Figure 3.4). Firstly, a beaker (1) containing distilled water (2) was put on the pan (3) of the balance. Next, a fine needle (4) was held partly submerged in the water with a clamp (5, 6) and the balance (8) was tared. Thereafter, the needle was taken out, and an experimental sample (7), surface dried on tissue paper, was suspended onto the needle. The sample was then submerged into the water so that the experimental sample was not in contact with the sides or bottom of the beaker. Afterwards, the weight of the sample volume was directly read and recorded on a four digit automatic balance. Thus, the saturated sample displaced an amount of water which was equal to its own volume in cubic centimetres (Olesen, 1971; Dinwoodie, 1981).

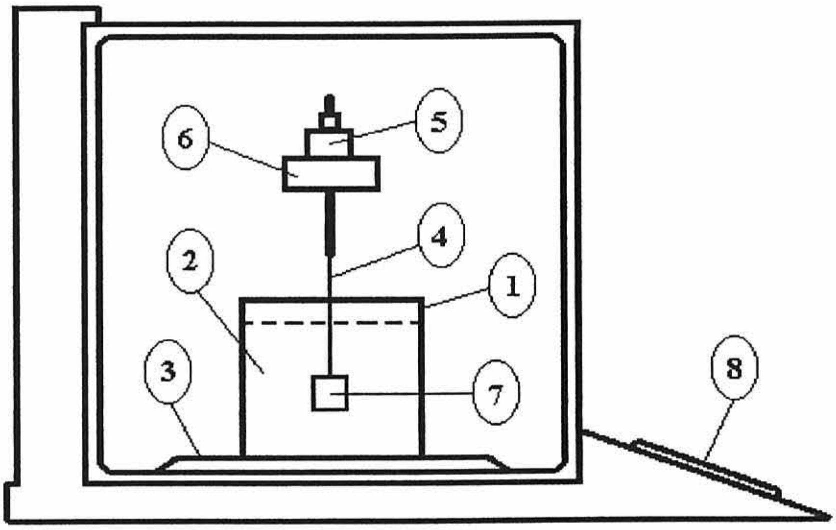


Figure 3.4. Recording the weight of the displaced volume of water during the measurement of basic density: 1, baker; 2, deionised water; 3, pan of the balance; 4, fine needle; 5, portable clamp for movement of the needle; 6, stable clamp for holding the needle platform; 7, experimental block; 8, indicator window of the balance.

Subsequently, all the samples were oven dried at 105 °C for 24 hours. After oven drying, the experimental samples were cooled in a desiccator charged with dry granulated silica gel and reweighed. After the measurement of the saturated and dried weights, density as detailed above (Equation 3.1) was calculated for each sample.

3.7 Determination of Permeability

A pilot experiment was run to determine suitable impregnation parameters. For this purpose rectangular samples (30 x 30 x 10 mm) were sealed on 4 faces leaving the transverse faces open so that liquid could penetrate from two opposing faces. Difficulty with orientation of rays and growth rings and machining was encountered with the rectangular samples prepared for the radial direction. The preparation for the rectangular samples to make the growth rings lie parallel each other on the transverse section was not exactly machined as required even if great care was taken. In later work cylindrical plug samples (30 x 15 mm diameter as detailed in section 3.4) were sealed, leaving only one face open, either the outer tangential face (i.e. that which was nearest to the bark) or a longitudinal face, so that penetration was restricted to one face.

In the main work of this study cylindrical (30 x 15 mm diameter) samples were prepared with their long axis in either the radial or longitudinal direction from the outer sapwood zone of each disc. In this way radial samples with ideal ray orientation could be prepared.

After kiln drying to a nominal 12 per cent, the plug samples were conditioned to an equilibrium moisture content of about 12 per cent in a constant temperature and humidity room set at 20 °C and 65% relative humidity.

Thereafter, the selected plugs were weighed and partially sealed with ABS (in a running fume cupboard) leaving either a tangential or longitudinal face open (Figure 3.5). The sealing compound for the purpose of handing large numbers of specimens was ABS polymer dissolved in methyl ethyl ketone[1] (Durapipe). This compound adhered well to the wood (provided the first coat was applied in a fairly dilute, low viscosity condition) and set very quickly. The final seal was strong and elastic enough to withstand liquid pressure of 100 psi (7 bar) and to accommodate lateral swelling. The coating was done three times to achieve a good seal. After reconditioning (as above) the sealed plugs were reweighed.

[1] To avoid exposure to vapour of methyl ethyl ketone coating was done in a running fume cupboard.

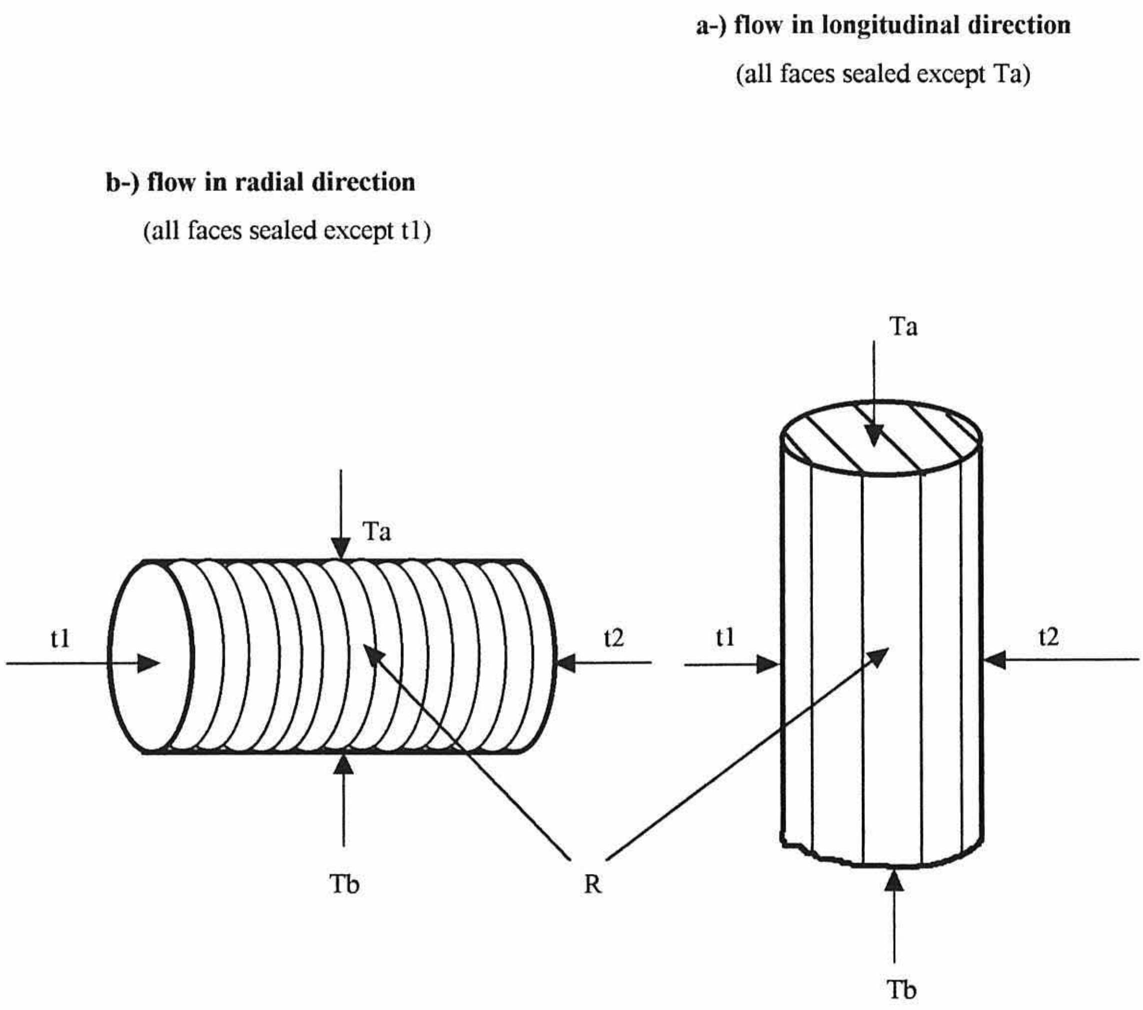


Figure 3.5. Sealing of plugs for the examination of preservative uptake and the depth of penetration: t1, outer zone of tangential face; t2, inner zone of tangential face; R, radial face; Ta, top of transverse face; Tb, bottom of transverse face.

3.7.1 Determination of Suitable Schedules

A full-cell process was carried out using different treatment schedules for radial and longitudinal samples because of the anisotrophy of flow. When timbers are impregnated with preservatives much better penetrations are obtained via the endgrain than laterally (across the grain). Therefore, suitable schedules for radial and longitudinal flow directions were determined in an initial trial experiment using locally grown Sitka spruce, Queen Charlotte Islands (QCI) provenance, from Beddgelert Forest.

A small scale laboratory treatment plant 600 mm long, 235 mm in diameter and with a fluid capacity of 44 litres was used for the experimental work (Figure 3.6). The pressure in this plant is applied by gas pressure from a nitrogen cylinder.

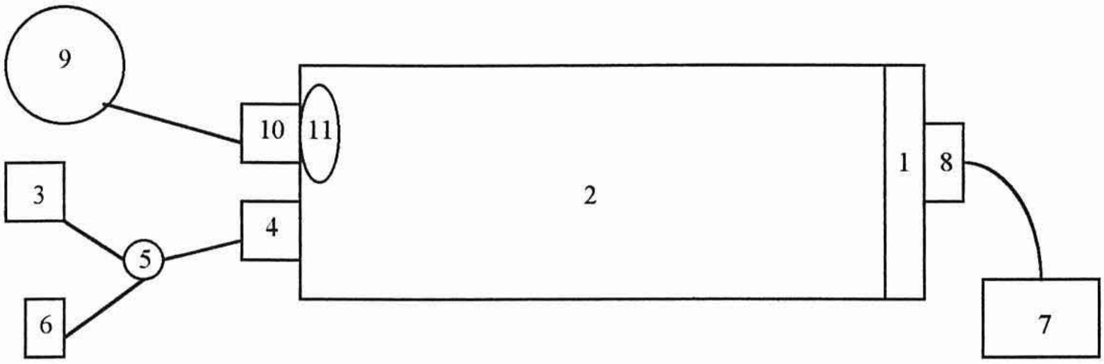


Figure 3.6. Layout of the preservation cylinder for the full cell treatment process: 1, cylinder door; 2, preservation cylinder; 3, vacuum pump; 4, vacuum valve; 5, vacuum trap; 6, mercury manometer; 7, preservative tank; 8, door valve for transferring the preservative; 9, nitrogen gas cylinder; 10, pressure valve; 11, pressure gauge.

A 2% CCA (Commercial Tanalith C, Hicksons) was prepared and checked by hydrometer for concentration (BS 4072, 1987 part 1). This was used throughout the experimental work. The full cell experimental schedules used were: initial vacuum 15 minutes at -0.84 bar (640 mm Hg) and various pressure periods (Table 3.3). No final vacuum was applied.

Table 3.3. The trial schedules for radial and longitudinal directions

parameters	radial	longitudinal
pressure (bar)	5	3
times (min.)	5, 15,45, 60	3, 6, 9

Determination of the Preservative Uptake and the Degree of Penetration

After the treatment the plugs were put on absorbent paper for a few seconds prior to weighing (to 3 significant figures). Thereafter, the fluid uptake was calculated (Equation 3.3), and fluid retention was determined on a whole-block basis (Equation. 3.4):

fluid uptake (g) = [treated weight (g) - sealed weight (g)] (3.3)

fluid retention (g/g) = [fluid uptake (g) / unsealed weight (g)] (3.4)

Plugs of different provenances vary in density which is an important factor which influences the amount of liquid that can be absorbed in a given block volume and influences the way preservative retention is expressed. Therefore a further assessment was made in relation to the maximum theoretical possible uptake of each plug based on void volume. This takes into account the density. The amount of space available in each plug was calculated as an estimation of the maximum volume of preservative which could be absorbed by wood (Mc Quire, 1970). This was calculated from the following equations:

volume of sample (m^3) = [π x (radius of the sample)^2 x length of the sample] (3.5)

wood cell wall (%) = [density of sample (kg/m^3) / 1500] (3.6)

void volume (m3) = [1 - wood cell wall] x 1000 (3.7)

Thus the maximum possible preservative uptake of a plug and other related values were calculated as follows:

preservative uptake (g/m^3) = [fluid uptake (g) / volume of sample (m^3)] (3.8)

void volume filled (%) = [preservative uptake (g/m^3) / void volume (m^3)] (3.9)

net dry salt retention (kg/m^3) = [solution strength (2%) / volume of sample (m^3)] (3.10)

After fixation, plugs were dried and cut longitudinally through the centre and copper penetration was determined by spraying a 1 % solution of Chrome Azurol-S on the cut surface and observing the blue colour indicative of copper (BS4072, 1987). The preservative penetration was then measured by image analyser as depth (mm) and as total treated area (%).

Results and Discussion

The results of different treatment schedules for radial and longitudinal flow directions are shown in Table 3.4 and are plotted in Figure 3.7a and b.

Table 3.4. The mean value of the fluid uptake and the fluid retention according to the trial treatment schedules for radial and longitudinal flow (initial vacuum: - 0.84 bar for 15 min).

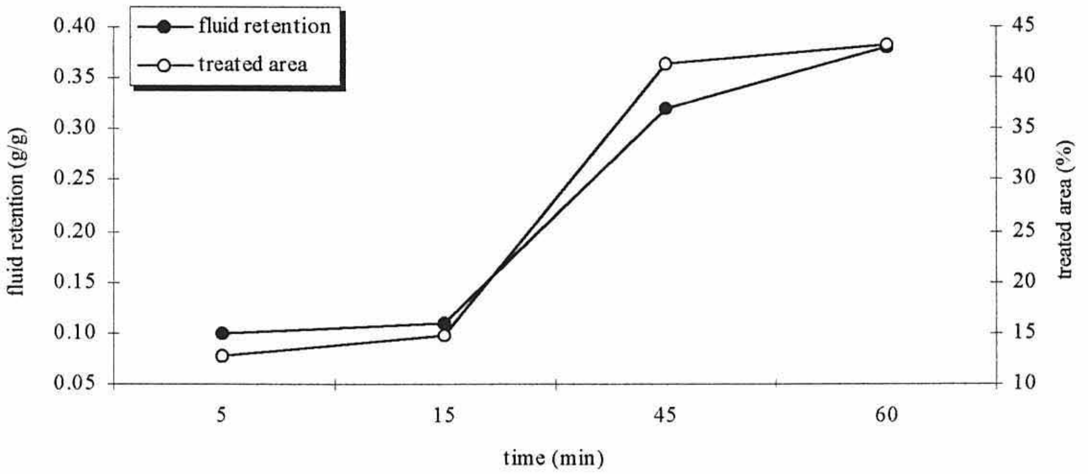
	schedule			preservative uptake		penetration	
		pressure	time	uptake	retention	depth	area
flow	code	(bar)	(min)	(g)	(g/g)	(mm)	(%)
	R1	5	5	0.26	0.10	3.2	12.70
radial	R2	5	15	0.34	0.11	3.3	14.87
	R3	5	45	0.93	0.32	10.9	41.38
	R4	5	60	1.03	0.38	12.4	43.15
	L1	3	3	1.49	0.48	10.8	52.62
longitudinal	L2	3	6	2.25	0.84	13.2	75.71
	L3	3	9	2.42	0.86	17.4	81.61

The trial results generally showed that the fluid retention is, as expected, markedly greater in the longitudinal flow direction despite the shorter period and lower pressure to the longitudinal samples. The results also showed that retention was higher in the longer treatment time. The fluid retention (g/g) increased from 0.48 to 0.86 as the time increased from 3 to 9 min on longitudinal penetration, and increased from 0.10 to 0.38 with increasing of the time from 5 to 60 min on radial penetration.

The ranges of fluid retention (FR) values were very close to each other in the radial samples treated for 45 minutes with the lowest standard deviation, and they were also the second most treated by the preservative according to the other experimental samples. Conversely, the actual values of the FR created quite large range between each other in the radial samples which treated for either 5 or 15 minutes with the highest standard deviations, and both of these experimental samples were the least treated. The ranges of FR were narrow in the longitudinal samples treated for 6 minutes with the low standard deviation, and the mean of the actual values of this samples was the second in the standing order. On the other hand, these considered ranges were a little wider in the longitudinal samples treated for 3 minutes with the high standard deviation, and its FR was the least according to the mean values.

It can be inferred from the experimental results that the longitudinal penetration of longer time was obviously greater than the shorter time under the same condition (3 bar pressure) of the treatment process. It appears that as the period increased the more preservative were driven into the wood capillary system where the preservative flowed more effectively from one tracheid lumen to another via unaspirated bordered pits. This resulted in complete saturation or the more fillings of the void volumes along the grain. However, if voids were occupied by extractive or blockages of flow pathways by resins (i.e. in radial direction), the flow of the preservative would not be greater even by doubling the period increase.

(a) Radial treatment of cylindrical samples (5 bar pressure was applied)



(b) Longitudinal treatment of cylindrical samples (3 bar pressure was applied)

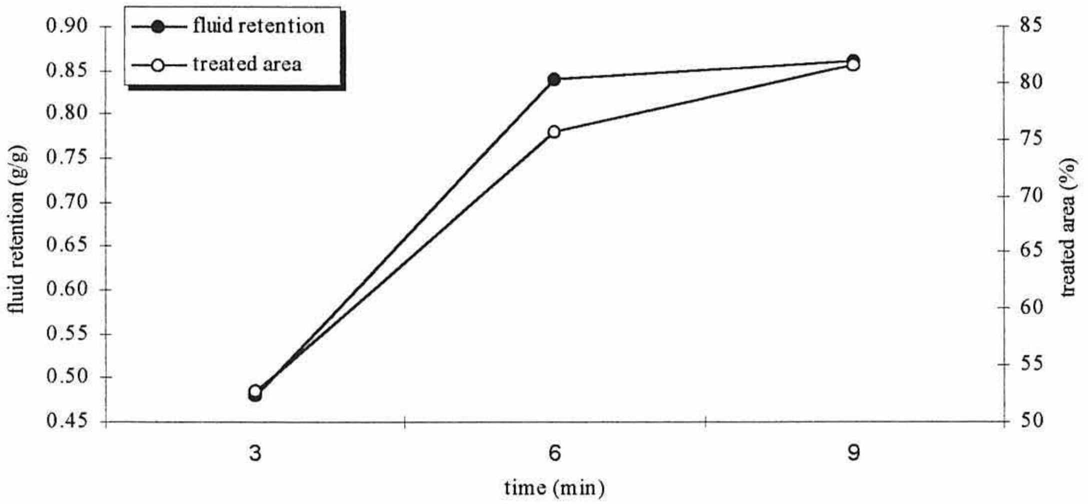


Figure 3.7. Trial to determine a suitable schedule for (a) radial, (b) longitudinal treatment of cylindrical samples: comparison of changes in the fluid retention and the treated area.

From the data (Table 3.4, Figures 3.7a and b) it was concluded that the suitable schedules are 5 bar pressure for 45 minutes for the radial direction, and 3 bar pressure for 7 minutes for the longitudinal direction. Therefore these schedules were used to examine the permeability of the different seed origins in both radial and longitudinal directions.

3.8 Data Recording and Statistical Analysis

The procedure of the data recording was well explained in sections 3.5, 6 and 7.

3.8.1 Statistical Analysis

All statistical analysis was conducted using the statistical package MINITAB, version 10.51 (Minitab Inc. Minitab for Windows, 1995). Arithmetic calculations and graphical designs were performed using the spreadsheet program Excel 5.0 for Windows.

Density and permeability data were tested for normality using the Ryan-Joiner test (Minitab 10.51). The normal scores of the data were compared with the experimental data by correlation analyses. The hypothesis of normality was rejected if the calculated correlation coefficient was below a critical value obtained from tables. Correlation analyses was made between the variables diameter, ring width, density, and the percentage of void volume filled in both longitudinal and radial flow directions at height, tree and seed origin levels. Minitab was also used for analysis of variance (ANOVA) and for regression analyses. Tukey pairwise comparison tests were performed to identify significant differences between treatment means.

Balanced analyses of variance (Balanced ANOVA) was also used to examine the relative importance of the factors influencing permeability with all possible interactions. It was possible to fully analyse this dataset beyond the calculation of sums of squares because there were no missing values in subclasses for three and four way interactions. The significance of three and four way interactions were determined by manually calculating variance ratios. A more detailed analysis was performed by excluding the three and four way interactions.

Table 3.4. Explanation of significance levels.

		p - level	p - indication	p - commendation
p	>	0.050	NS	Not Significant
p	≤	0.050	*	Significant
p	≤	0.010	**	Highly Significant
p	≤	0.001	***	Very Highly Significant

4 RESULTS

In this chapter, the measured variables (dbh diameter of the selected trees, mean growth ring width [Grw] on the transverse section of the experimental plug samples), and the experimental results (wood density, the percentage of void volume filled in either longitudinal [LVVF%] or radial [RVVF%] flow directions) have been reported as to means of each seed origin grown in both sites.

All the considered parameters were compared initially on overall means for both Rhondda and Dalby, and then for each site (4.1). The experimental data were then analysed by balanced analysis of variance (4.2) to examine the relative importance of the factors influencing diameter, GRw, density, LVVF% and RVV% with all possible interactions (site, seed origin, site x seed origin, trees within site and seed origin, height, seed origin x height, and height in trees within site and seed origin).

The experimental results of density (4.3) and permeability (4.4) were then particularly explained according to the factors which significantly effect them. The relationships between the variables were then investigated by correlation analysis (4.5).

4.1 Comparison of Means

Tree diameter (dbh), mean growth ring width (GRw) and the mean results of both density and permeability trials (i.e. the percentage of void volume filled for both longitudinal and radial flow directions, LVVF% and RVVF% respectively) are given in Table 4.1a. The results have been shown as overall means for each seed origin at both sites.

The tree diameters varied from 11.3 cm with Alaska (AL) to 14.5 cm with California (CA). Mean Grw on the experimental samples ranged from 3.6 mm to 5.8 mm. Although the proportion of latewood to earlywood on the experimental samples have not been measured in this study, the seed origin North Washington (NW) showed the narrowest ring width whereas CA showed the widest GRw. This was therefore reflected in wood density which was the greatest in NW (434.1 kgm^{-3}), and the lowest in CA (366.2 kgm^{-3}).

The LVVF and RVVF spread also differed significantly among seed origins ($p \leq 0.05$). The values were most in Queen Charlotte Island (QCI, 63.9 %, 24.6 %) and least in North Oregon (NO, LVVF% 50.9 %) and South Oregon (SO, RVVF% 14.7 %).

Table 4.1a. The overall means of the variables for both Rhondda and Dalby.

site	diameter cm	GRw mm	density kgm^{-3}	LVVF %	RVVF %
Alaska	11.3	4.3	421.8	54.7	20.6
British Colombia	13.2	4.3	387.1	56.3	18.9
Queen Charlotte Island	14.4	4.3	411.6	63.9	24.6
North Washington	12.8	3.6	434.1	63.9	19.7
South Washington	13.1	3.7	422.6	59.9	16.1
North Oregon	12.7	4.2	424.4	50.9	17.7
South Oregon	12.9	3.9	426.0	61.9	14.7
California	14.5	5.8	366.2	56.6	17.4
mean	13.1	4.2	411.7	58.5	18.6

diameter = diameter of the sampled disc (cm), density = density of the experimental sample (kgm^{-3}), ring width = mean growth ring width (mm), LVVF = void volume filled (VVF) in longitudinal direction (%), RVVF = the percentage of VVF in radial direction.

These results can also be examined by site, e.g. Rhondda and Dalby (Tables 4.1b and c, respectively). The means shown here are of data from 5 trees per seed origin and 3 heights per tree in each site. The full results are given in Appendix 1.

The tree growth varied significantly among most of the seed origins in either sites. The diameter (dbh) varied from 11.5 cm to 13.6 cm in Rhondda, and 11.2 cm to 16.0 cm in Dalby. In both sites, the seed origin Alaska (AL) had the narrowest tree diameter while the widest was California (CA) in Rhondda and Queen Charlotte Island (QCI) in Dalby.

Mean growth ring width (GRw) was largest in seed origin CA in both sites (Rhondda [Rh]: 6.1 mm, Dalby [Da]: 5.6 mm). On the other hand, the narrow growth ring occurred in different seed origins, i.e. GRw was 3.9 mm in North Washington (Rhondda) and 3.1 mm in AL (Dalby).

The total amount of latewood directly influenced density values. The seed origins SO (Rhondda) and AL (Dalby), which of both had the highest amount of latewood (Lw), had also the greatest density (458.1 kgm^{-3}, 449.3 kgm^{-3}), whereas CA which had the lowest Lw, also had the lowest density in both sites (371.2 kgm^{-3}, 361.3 kgm^{-3}).

The seed origin North Oregon (NO) showed the lowest longitudinal permeability in both sites (Rh: 43.2 %, Da: 58.6 %) whereas NW (59.4 %) in Rhondda and South Oregon (SO, 71.0 %) in Dalby were the most permeable ones. For radial permeability, QCI was the most permeable from either site (Rh: 25.4 %, Da: 23.8 %) while seed origins SO (15.6 %) in Rhondda and South Washington (SW, 12.3 %) in Dalby had the lowest permeability. Overall the second most permeable seed origins in terms of LVVF% and RVVF% were QCI and AL, respectively. Both of the two seed origins were second greatest in either Rhondda (QCI: 58.8 %, AL: 23.9 %) or Dalby (QCI: 69.0 %, AL: 17.3 %).

Table 4.1b. Means of the variables for trial site Rhondda.

site	diameter cm	GRw mm	density kg/m^3	LVVF %	RVVF %
Alaska	11.5	5.4	394.3	50.9	23.9
British Colombia	12.4	5.0	382.8	49.7	21.8
Queen Charlotte Island	12.8	4.9	422.6	58.8	25.4
North Washington	12.0	3.9	446.6	59.4	22.9
South Washington	12.8	4.1	430.2	58.8	19.9
North Oregon	12.9	5.1	418.6	43.2	18.1
South Oregon	12.2	4.2	458.1	52.8	15.6
California	13.6	6.1	371.2	52.9	17.6
mean	12.5	4.8	415.6	53.3	20.6

Table 4.1c. Means of the variables for trial site Dalby.

site	diameter cm	GRw mm	density kg/m^3	LVVF %	RVVF %
Alaska	11.2	3.1	449.3	58.5	17.3
British Colombia	13.9	3.5	391.4	62.9	15.9
Queen Charlotte Island	16.0	3.6	400.5	69.0	23.8
North Washington	13.5	3.5	421.7	68.5	16.4
South Washington	13.3	3.2	415.0	61.1	12.3
North Oregon	12.6	3.3	430.2	58.6	17.3
South Oregon	13.6	3.5	393.9	71.0	13.8
California	15.4	5.6	361.3	60.2	17.2
mean	13.7	3.7	407.9	63.7	16.7

4.2 Analysis of Variance

The experimental data were analysed by balanced analysis of variance according to site, seed origin, site x seed origin, trees within site and seed origin, height, seed origin x height, and height on trees within site and seed origin. Table 4.2 shows the summary results of analysis of variance.

Variations in diameter, mean ring width (GRw), density, the percentage of longitudinal and radial void volume filled (LVVF%, RVVF%) among trees of different sites (S), seed origins (O), interactions of the sites and seed origins (S x O), trees within sites and seed origins T(S O), and tree heights (H) were very highly significant ($p < 0.01$).

The height x site interaction (H x S) and the height x seed origin interaction (H x O) was highly significant for diameter and void volume filled in either of the two flow directions, although was not significant in the case of ring width. Further, the effects of H x O was also highly significant for density, whereas the height x site interaction (H x S) was not.

Table 4.2. Summary of results of analysis of variance for permeability trial indicating significant effects ($p \leq 0.050$) for the influencing factors.

source	diameter cm	GRw mm	density kg/m^3	LVVF %	RVVF %
S	***	***	***	***	***
O	***	***	***	***	***
S x O	***	***	***	***	**
T(S O)	***	***	***	***	***
H	***	***	***	***	***
H x S	***	NS	NS	***	***
H x O	***	NS	***	***	***
H x S x O	***	**	NS	NS	***
H x T(S O)	***	*	***	***	***

S = site, O = seed origin, T = tree, H = height, x = indication of interactions, NS = not significant, * significant at 95% level, *** significant at 99% level, *** significant at 99.9% level.

4.3 Density

As was seen in Table 4.2, there were significant differences in density between site (S), seed origin (O) and height (H). The site x seed origin interaction (S x O), and height x seed origin interaction (H x O) were also highly significant for density.

There were also significant differences in density between trees within site and seed origin [T(S O)] and height on trees within site and seed origin [H x T(S O)] but there were no effect of height x site interaction (H x S), and height in seed origin with site (H x S x O).

4.3.1 Density / *Site*

Means for density of each seed origin at Rhondda and Dalby are given in Table 4.3 with the indication of significance between the seed origins within the sites. All these data are listed against seed origins as similar range as the natural distribution of Sitka spruce grown from north to south (from Alaska to California).

As is shown in Table 4.3, there were significant differences ($p = 0.035$) in density between the sites where Rhondda (415.6 kgm^{-3}) was greater than Dalby (407.9 kgm^{-3}).

Table 4.3. Pairwise differences in density between origins (Rhondda, Dalby, overall mean).

	density (kgm^{-3})		
seed origin	Rhondda	Dalby	overall means
Alaska	394.3^{ac}	449.3^{a}	421.8^{ad}
British Colombia	382.8^{a}	391.4^{b}	387.1^{b}
Queen Charlotte Islands	422.3^{bd}	400.5^{bc}	411.6^{a}
North Washington	446.6^{be}	421.7^{cd}	434.1^{d}
South Washington	430.2^{bd}	415.0^{bcd}	422.6^{ad}
North Oregon	418.6^{cd}	430.2^{ad}	424.4^{ad}
South Oregon	458.1^{e}	393.9^{b}	426.0^{ad}
California	371.2^{a}	361.3^{e}	366.2^{c}
• • mean	415.6	407.9	412

• Means that are not significantly different from each other at $P<0.05$ level have the same superscript in a given column. (e.g. in Rhondda, British Colombia 383^{a} is not significantly different to California 371^{a}).
• • Also overall means of each site are significantly different from each other at $P<0.05$ level.

According to the overall means of the density, the results generally indicate that the material from Washington (NW, SW) and Oregon (NO, SO) seed origins had the higher density while both British Colombia (BC) and California (CA) had the lower densities.

The highest density (kgm^{-3}) occurred in NW (434) followed by SO (426), NO (424) and SW (423) whereas the low densities were found in both CA (366) and BC (387). Although, the densities of both AL (422) and QCI (412) were notably greater than either BC or CA, they were slightly lower than those for NW, SO, NO and SW.

The seed origin CA (366) was highly significantly different from all of the other seed origins having the lowest density. BC (387) had the second lowest density and also differed from the other. It also seemed that although the difference of density between QCI (412) and NW (434) was statistically significant, there were no more significant differences between the other seed origins (Table 4.3).

4.3.2 Density / *Seed Origin*

Rhondda

As seen in Table 4.3, the highest density (kgm^{-3}) in Rhondda was in SO (458) followed by NW (447) and SW (430) whereas it was the lowest in CA (371). The descending order of density for remaining seed origins was QCI (422), NO (419), AL (394), and BC (383).

The average density of SO (458) significantly higher than all the seed origins except NW (447), and the density of CA (371) was significantly lower than all the other seed origins. The difference between BC (383) and CA (371) was not statistically significant.

On the other hand, mean densities of NW (447), SW (430) and QCI (423) were significantly greater than both AL (394) and BC (383). Density of NO (419) was significantly different to the seed origins SO (458), QCI (422), NW (447), BC (383) and CA (371). It also appears that density in NO (419) was significantly lower than in SO (458), QCI (422) and NW (447) but greater than both in BC (383) and CA (371).

Dalby

As also shown in Table 4.3, the greatest density in Dalby was in AL (449) followed by NO (430) and NW (422), whereas it was the lowest in CA (361). The descending order of density for the others was SW (415), QCI (401), SO (394), and BC (391).

The average density of AL (449) was significantly higher than all the other seed origins (BC, QCI, NW, SW, NO, SO and CA) but only the differences in density between AL (449) and NO (430) were not statistically significant. The average density of CA (361) was significantly lower than all the seed origins.

The density of BC (391) was significantly lower than both in NO (430) and NW (422), and density in NO (430) was also significantly higher than both in QCI (401) and SO (394). Furthermore, there was a significant difference between density in the seed origins NW (422) and SO (394). Although NW (422) and QCI (401) may appear to be different to each other, this was not statistically significant.

4.3.3 Density / *Site* x *Seed Origin - Interactions*

Interactions between origins and sites are highlighted by ranking origins in descending order of density from highest to lowest at each site.

As is seen in Figure 4.1, seed origins were individually denser on one site than another and the descending order of the densities varied between the sites. For instance, the mean densities of the Rhondda trees of SO, NW, SW, QCI and CA were significantly higher than that of the Dalby trees, whereas the seed origins of AL, NO and BC were less dense in Rhondda than in Dalby. Besides, both BC and CA showed lower densities in either site.

Figure 4.1. Site x Seed Origin interactions for density.

	Rhondda	Dalby	
458.1	SO	AL	449.3
446.6	NW	NO	430.2
430.2	SW	NW	421.7
422.3	QCI	SW	415.0
418.6	NO	QCI	400.5
394.3	AL	SO	393.9
382.8	BC	BC	391.4
371.2	CA	CA	361.3

4.3.4 Density / *Tree within Seed Origin* / *Tree Height*

The overall means of density for each seed origin at both sites are shown in Table 4.4a according to the selected heights (1.3, 2.3 and 3.3 m) of the trial trees. The results are also individually given for Rhondda and Dalby in Table 4.4b and c, respectively. The results of seed origin x height interaction is shown in Figure 4.2 a, b and c according to the tree heights from apex to the base at 3.3, 2.3 and 1.3 m levels.

As is given in Table 4.4a, density in mature wood of Sitka spruce was found to be slightly greater at breast height (1.3 m) than higher in the tree. This differences became more noticeable with increasing distance from breast height at either 2.3 m or 3.3 m height of the tree. Comparing the results of density at the different heights (i.e. 2.3 m and 3.3 m), it appears that density declines with increasing height in stem, such changes with height in a tree differed in each seed origins on a base of the overall mean data for both sites.

The rate (%) of decrease in density between the base (1.3 m) and the centre (2.3 m) height of the tree was greatest in CA (6.7) followed by AL (4.1) while was lowest in either SO (0.2) or NW (0.2) in despite of NO (0.0) where there was not any changes. The descending order of the rates of change in density for the others was SW (2.7), QCI (1.9) and BC (1.7). Likewise, the rate of change in density between base (1.3 m) and the top (3.3 m) height of the tree was greatest in CA (8.8) followed by SW (7.0) and was lowest in NO (2.5) with

QCI (2.6) and AL (2.7). The descending order for others was SO (5.9), NW (4.3) and BC (3.5). The differences in density between the heights at 2.3 m and 3.3 m followed same trend of a decrease with an increase height in the stem. It only increased in AL (1.4) among the seed origins. The change of density was greatest in SO (5.7) followed by SW (4.4) and was lowest in QCI (0.7). Moreover, in the descending order of the rate of decline in density for the others was NW (4.0), NO (2.5), CA (2.2) and BC (1.8).

Table 4.4a. Overall means of density at tree heights in eight origins of both sites.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	432	414	420	422
British Colombia	394	387	380	387
Queen Charlotte Islands	418	410	407	412
North Washington	441	440	422	434
South Washington	437	425	406	423
North Oregon	428	428	417	424
South Oregon	435	434	409	426
California	386	360	352	366
mean	421	412	402	412

Table 4.4b. Mean density at tree heights of seed origins in Rhondda

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	401	387	395	394
British Colombia	389	381	379	383
Queen Charlotte Islands	426	425	416	423
North Washington	456	454	430	447
South Washington	442	434	414	430
North Oregon	418	417	422	419
South Oregon	469	465	441	458
California	394	362	358	371
mean	425	416	407	416

Table 4.4c. Mean density at tree heights of seed origins in Dalby

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	462	441	444	449
British Colombia	399	393	382	391
Queen Charlotte Islands	409	395	398	401
North Washington	425	426	414	422
South Washington	432	415	398	415
North Oregon	439	439	413	430
South Oregon	400	404	377	394
California	379	358	347	361
mean	418	409	397	408

Figure 4.2a. Site x Origin interactions for density at 3.3 m height.

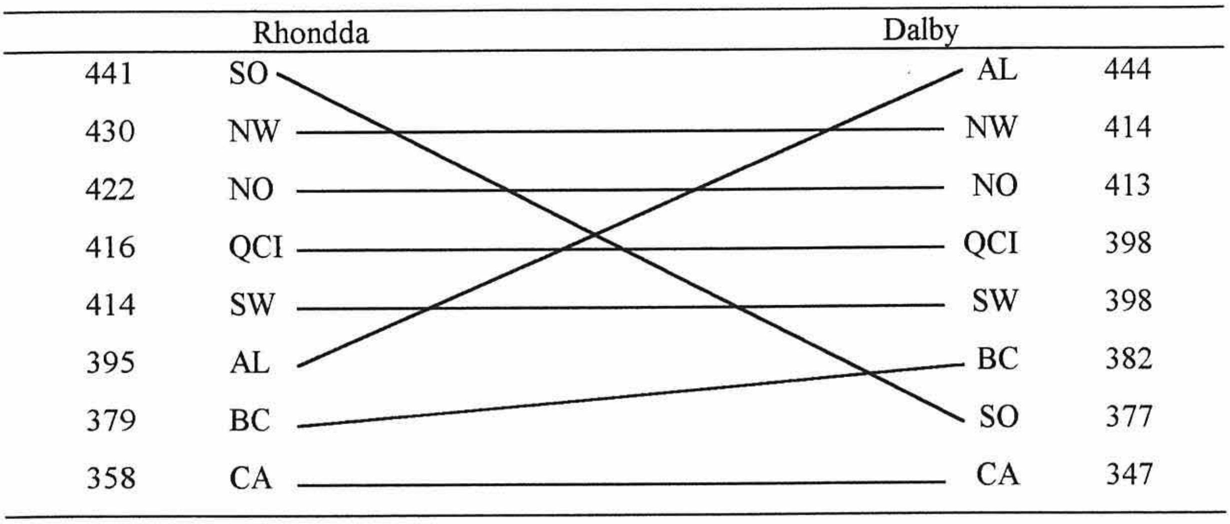


Figure 4.2b. Site x Origin interactions for density at 2.3 m height.

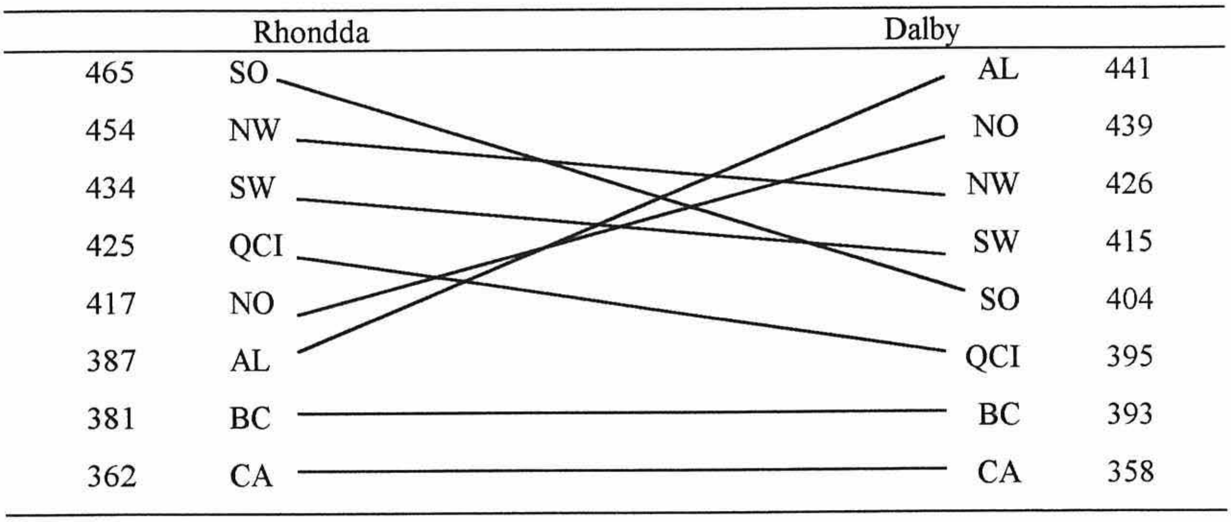
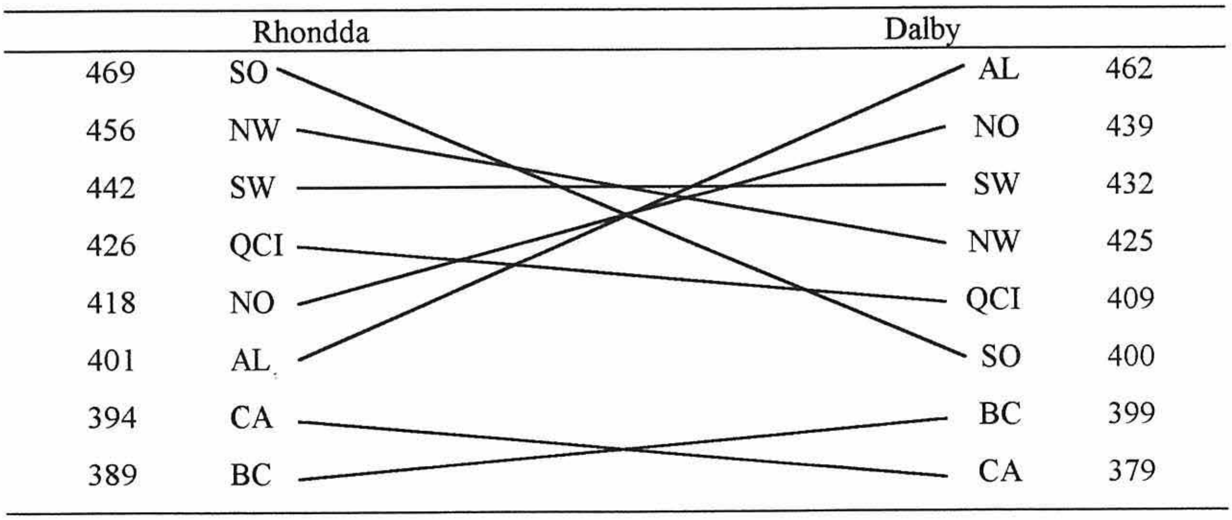


Figure 4.2c. Site x Origin interactions for density at 1.3 m height.



4.4 Permeability

In both longitudinal and radial flow directions, the percentage of void volume filled (LVVF%, RVVF%) were significantly affected by sites, seed origins, interactions of sites and seed origins, and trees within sites and seed origins. The effects of height, height x site interaction, height x seed origin interaction, and height on trees within sites and seed origins were also significant in either of the two flow directions. However, there was no effect of height in seed origins with sites in LVVF% comparing to RVVF%.

4.4.1 Permeability / *Site*

Means of LVVF% and RVVF% of each seed origin at Rhondda and Dalby are given in Table 4.5a and b respectively with the indication of significance (i.e. pairwise differences) between the seed origins within the sites. These data are means of the forty trees per site and listed against seed origins as similar range as the natural distribution of Sitka spruce which grown from north to south (from Alaska to California). In each of the tables, the overall means of each seed origin in both site were also included.

As is shown in Table 4.5a and b, there were significant differences ($p = 0.001$) in both LVVF% and RVVF% between the sites where LVVF% was higher in Dalby (63.7) than in Rhondda (53.3) while RVVF% was much greater in Rhondda (20.7) than in Dalby (16.8).

It can be inferred from the results given above that the percentage of void volume filled by liquid occurred notably different in either flow directions and inversely change in each site. The general view of the trend showed that the trees of Rhondda were more treated radially as compared to Dalby trees, although they were less treated longitudinally.

Table 4.5a. Pairwise differences of LVVF% between seed origins in Rhondda and Dalby.

origins	Rhondda	Dalby	overall
Alaska	50.9^{abc}	58.5^{a}	54.7^{ac}
British Colombia	49.7^{bc}	62.9^{ab}	56.3^{acd}
Queen Charlotte Islands	58.8^{a}	69.0^{b}	63.9^{b}
North Washington	59.4^{a}	68.5^{b}	63.9^{b}
South Washington	58.8^{a}	61.1^{a}	59.9^{ab}
North Oregon	43.2^{b}	58.6^{a}	50.9^{c}
South Oregon	52.8^{ac}	71.0^{b}	61.9^{bd}
California	52.9^{ac}	60.2^{a}	56.6^{acd}
• • mean	53.3	63.7	58.5

• Means that are not significantly different from each other at $P<0.05$ level have the same superscript in a given column. (e.g. in Rhondda, QCI 58.8^{a} is not significantly different to NW 59.4^{a}).
• • Also overall means of each site are significantly different from each other at $P<0.05$ level.

Table 4.5b. Pairwise differences of RVVF% between seed origins in Rhondda and Dalby.

origins	Rhondda	Dalby	overall
Alaska	23.9^{ac}	17.4^{ab}	20.7^{ab}
British Colombia	21.9^{ab}	15.9^{a}	18.9^{ad}
Queen Charlotte Islands	25.4^{a}	23.8^{b}	24.6^{b}
North Washington	22.9^{ab}	16.5^{ab}	19.7^{abd}
South Washington	19.9^{ab}	12.4^{a}	16.2^{ac}
North Oregon	18.1^{ab}	17.4^{ab}	17.8^{ac}
South Oregon	15.7^{b}	13.8^{a}	14.8^{cd}
California	17.6^{bc}	17.2^{ab}	17.4^{ac}
• • mean	20.7	16.8	18.8

• Means that are not significantly different from each other at $P<0.05$ level have the same superscript in a given column. (e.g. in Dalby, BC 15.9^{a} is not significantly different to SO 13.8^{a}).
• • Also overall means of each site are significantly different from each other at $P<0.05$ level.

According to the overall means of both LVVF% and RVVF% which given in Table 4.5, it can be seen that the seed origins from the centre region of the natural distribution (QCI, NW and SW) and also one of the southern seed origin (SO) are more permeable longitudinally, although the northern (AL and BC) and the southern (CA, NO) seed origins were less permeable in longitudinal flow direction. On the other hand, the seed origins from the centre region of the natural distribution (QCI and NW) and the northern seed origins (AL and BC) were more permeable radially, whereas the southern seed origins (NO, SO and CA) and also SW from the centre region were less permeable in the radial direction

The LVVF% was considerably higher in both QCI (63.9) and NW (63.9) followed by SO (61.9) and SW (59.9). In the mid range were CA (56.6) and BC (56.3) which were close to AL (54.7) while lowest was NO (50.9). The RVVF% was notably greater in QCI (24.6) followed by AL (20.7), NW (19.7) and BC (18.9), slightly lower in either NO (17.8) or CA (17.4) and also in SW (16.2) whereas was the lowest in SO (14.8).

The most longitudinally permeable seed origins QCI (63.9) and NW (63.9) were highly significantly different to the less permeable seed origins CA (56.6), BC (56.3), AL (54.7) and NO (50.9). The next most permeable, SO (61.9), was significantly different to both AL (54.7) and NO (50.9), although the third, SW (59.9), was only significantly different to NO (50.9). However, the most radially permeable QCI (24.6) was very highly significantly different to all the other seed origins except AL (20.7). AL (20.7) was only notably significantly different to SO (14.8.

4.4.2 Permeability / *Seed Origin*

Rhondda

As can be seen in Table 4.5a, the highest LVVF% was in NW (59.4) followed by SW (58.8) and QCI (58.8) whereas it was the poorest in NO (43.2) among the other seed origins, i.e. the descending order of the LVVF% for the remainder seed origins was CA (52.9), SO (52.8), AL (50.9), BC (49.7).

Mean LVVF% of NW (59.4), SW (58.8) and QCI (58.8) were significantly greater than both BC (49.7) and NO (43.2). The average LVVF% of both CA (52.9) and SO (52.8) was also statistically significant to NO (43.2). There were no significant differences in LVVF% between the other seed origins although the differences between SO (52.8) and AL (50.9) were close to being statistically significant.

As can be seen in Table 4.5b, the highest RVVF% was in QCI (25.4) followed by AL (23.9) and NW (22.9) whereas it was the lowest in SO (15.7) among the other seed origins, i.e. the descending order of the RVVF% for the remainder seed origins was BC (21.9), SW (19.9), NO (18.1), CA (17.6).

It appears that RVVF% of QCI (25.4) and AL (23.9) were significantly greater than SO (15.7). In addition, QCI (25.4) was also significantly different from CA (17.6). However, there were no significant differences in RVVF% between the other seed origins although the differences between BC (21.9) and SO (15.7) were close to being statistically significant.

Dalby

As seen in Table 4.5a, the highest LVVF% was in SO (71.0) followed by QCI (69.0) and NW (68.5) whereas it was the lowest in NO (58.6) and AL (58.5) among the other seed origins, i.e. the descending order of the LVVF% for the remainder seed origins was BC (62.9), SW (61.1), CA (60.2).

The mean LVVF% of both QCI (69.0) and NW (68.5) were significantly greater than both NO (58.6) and AL (58.5). Also, SO (71.0) was significantly higher than both SW (61.1), CA (60.2) and NO (58.6). There were no significant differences in LVVF% between the other seed origins although the differences between BC (62.9) and AL (58.5) were close to being statistically significant.

As can be seen in Table 4.5b, the highest RVVF% was in QCI (23.8) followed by AL (17.4) and NO (17.4) whereas it was the poorest in SW (12.4) among the other seed origins, i.e. the descending order of the RVVF% for the remainder seed origins was CA (17.2), NW (16.5), BC (15.9), SO (13.8).

The RVVF% in QCI (23.8) was significantly greater than BC (15.9), SO (13.8) and SW (12.4). There were no significant differences between the other seed origins although the differences between NW (16.5) and SW (12.4) were close to being statistically significant.

4.4.3 Permeability / *Site* x *Seed Origin - Interactions*

In general, the experimental trees of each seed origin were better treated longitudinally in Dalby and radially in Rhondda, although the percentage of void volume filled in both longitudinal and radial flow directions at each seed origin indicated different behaviour in particular trial sites (Figure 4.3a and b).

Although the LVVF% was greater in Dalby, values for both NW and QCI were above average and those for both AL and NO below average at both sites. There were however an inverse changes of LVVF% in either of the following seed origins SO, SW, BC and CA. Both SO and BC had higher LVVF% in Dalby whereas each of them had lower value in Rhondda where both SW and CA had greater amount of LVVF%.

On the other hand, QCI was the most treated radially followed by AL in either sites and SO was the least treated radially in Rhondda and was the second lowest in Dalby. The other seed origins (NW, BC, SW, NO and CA) showed an inverse pattern that NW, BC and SW had greater RVVF% in Rhondda than in Dalby where NO and CA more treated radially.

Figure 4.3a. Site x Origin interactions for LVVF%

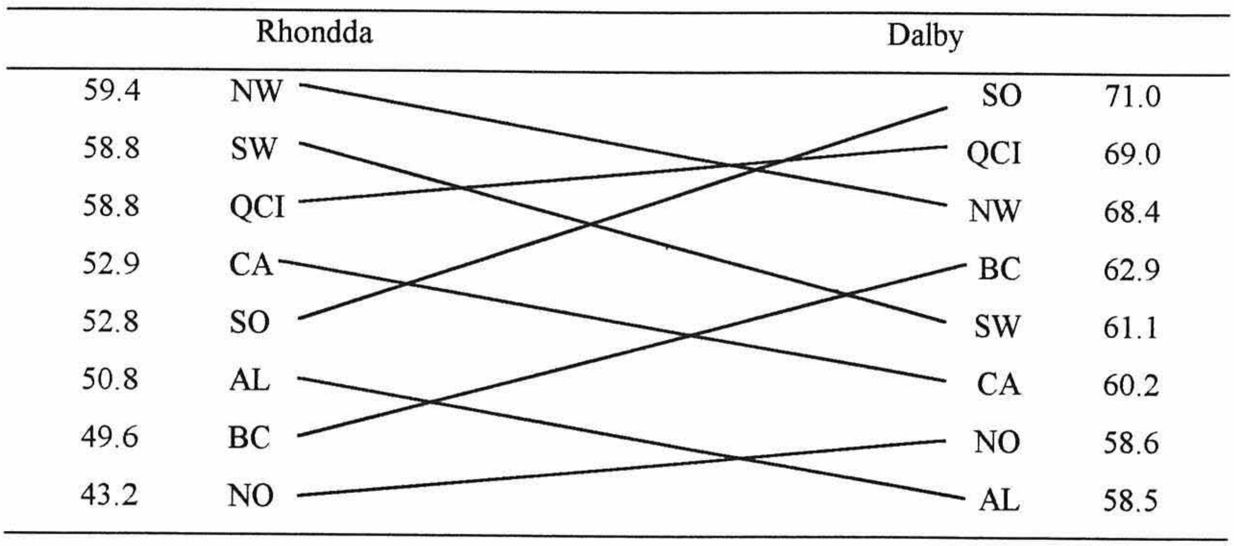
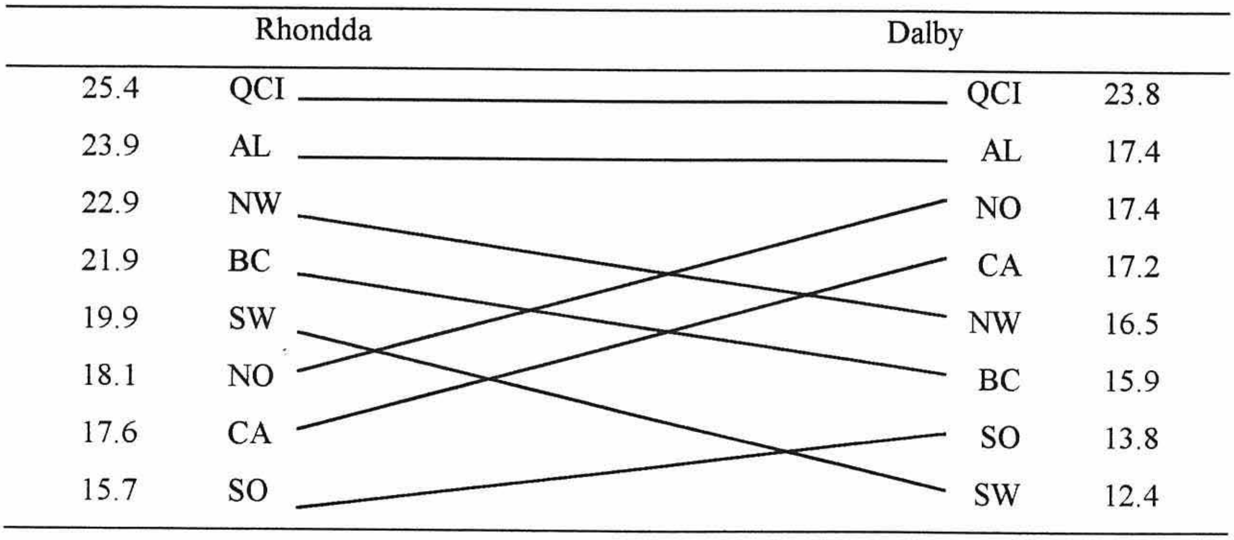


Figure 4.3b. Site x Origin interactions for RVVF%



4.4.4 Permeability / *Tree within Seed Origin / Tree Height*

The overall means of permeability on a basis of LVVF% and RVVF% for each seed origin at both sites are shown in Table 4.6a and 4.7a respectively according to the selected heights (i.e. 1.3, 2.3 and 3.3 m) in the experimental trees. These results are also given separately for Rhondda in Table 4.6b and 4.7b, and for Dalby in Table 4.6c and 4.7c. The interactions of height and seed origin for both LVVF% and RVVF% were also shown from apex to base of the selected trees in Figure 4.4a, b and c, and in Figure 4.5a, b and c, respectively.

As is given in Table 4.6a, the percentage of longitudinal void volume filled (LVVF%) was found to be higher at the centre of the tree than either of the other heights of the tree in all seed origins except BC and CA where there were an increasing trend of LVVF% with increasing of height up the tree.

The total percentage increase in LVVF% between the breast and top height of the tree was greatest in SW (8.6) followed by NO (8.1) and CA (8.0), and lowest in BC (6.3). Conversely, the decrease in LVVF% between the considered heights was highest in AL (20.8) followed by NW (13.0) and QCI (4.0), and was least in SO (1.3).

On the other hand, the variation of the percentage of void volume filled in radial flow direction (RVVF%) in mature wood of Sitka spruce within the tree was found to be considerable and did not follow the systematic trend as seen with LVVF%. However, it generally seemed in most of the trial seed origins (i.e. AL, BC, SW, NO and CA) that there was a decreasing trend from base (1.3 m) to the centre (2.3 m) of the tree, and an increasing trend from 2 m height to the top (3.3 m) of the tree, and in QCI these were inverse. In both NW and SO there were a decreasing trend with increasing height of the stem.

The greatest RVVF% occurred at breast (1.3 m) height in AL (27.2), NW (26.5), SW (20.2), SO (16.9) and CA (18.1), although at the top height (3.3 m) in BC (21.2) and NO (18.2), and at the centre (2 m) height in QCI (25.6).

The total rate of increase in RVVF% between the breast and top height of the tree was highest in NW (52.4) followed by SW (28.7), AL (27.9) and SO (20.1), and lowest in CA (2.2). In such seed origins, the RVVF% from base to apex of the tree seemed to change in both BC (9.8) and NO (4.0) whereas was no change in QCI (0.0).

Table 4.6a. Overall means of LVVF% at tree heights in eight seed origins of both sites.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	59.1	58.3	46.8	54.7
British Colombia	54.9	55.6	58.4	56.3
Queen Charlotte Islands	64.5	65.3	61.9	63.9
North Washington	65.4	69.5	56.9	63.9
South Washington	55.3	64.5	60.1	59.9
North Oregon	47.1	54.7	50.9	50.9
South Oregon	61.4	63.8	60.6	61.9
California	54.9	55.4	59.3	56.6
mean	57.9	60.9	56.9	58.5

Table 4.6b. Means of LVVF% at tree heights in eight seed origins of Rhondda.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	52.5	56.3	43.8	50.9
British Colombia	46.5	53.4	49.1	49.7
Queen Charlotte Islands	60.4	60.3	55.8	58.8
North Washington	59.1	66.7	52.4	59.4
South Washington	52.9	65.4	58.2	58.8
North Oregon	34.4	50.5	44.8	43.2
South Oregon	51.9	55.4	51.3	52.8
California	47.9	51.4	59.6	52.9
mean	50.7	57.4	51.9	53.3

Table 4.6c. Means of LVVF% at tree heights in eight seed origins of Dalby.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	65.6	60.3	49.7	58.6
British Colombia	63.4	57.8	67.8	62.9
Queen Charlotte Islands	68.6	70.3	68.1	69.0
North Washington	71.7	72.3	61.3	68.5
South Washington	57.8	63.6	61.9	61.1
North Oregon	59.8	58.8	57.2	58.6
South Oregon	71.0	72.1	69.9	71.0
California	62.1	59.5	59.1	60.2
mean	65.0	64.3	61.9	63.7

Table 4.7a. Overall means of RVVF% at tree heights in eight seed origins of both sites.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	27.2	15.3	19.6	20.7
British Colombia	19.3	16.2	21.2	18.9
Queen Charlotte Islands	24.1	25.6	24.1	24.6
North Washington	26.5	20.0	12.6	19.7
South Washington	20.2	13.9	14.4	16.1
North Oregon	17.5	17.5	18.2	17.8
South Oregon	16.9	13.9	13.5	14.8
California	18.1	16.5	17.7	17.4
mean	21.2	17.4	17.7	18.7

Table 4.7b. Means of RVVF% at tree heights in eight seed origins of Rhondda.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	32.3	20.5	19.0	23.9
British Colombia	23.4	19.3	22.9	21.9
Queen Charlotte Islands	27.2	30.9	18.1	25.4
North Washington	32.0	25.9	10.8	22.9
South Washington	27.3	16.5	15.9	19.9
North Oregon	20.9	18.7	14.7	18.1
South Oregon	23.2	14.4	9.5	15.7
California	20.4	13.5	19.0	17.6
mean	25.9	19.9	16.2	20.7

Table 4.7c. Means of RVVF% at tree heights in eight seed origins of Dalby.

seed origin	1.3 m	2.3 m	3.3 m	mean
Alaska	22.1	9.9	20.1	17.4
British Colombia	15.3	13.0	19.4	15.9
Queen Charlotte Islands	20.9	20.3	30.2	23.8
North Washington	21.0	14.1	14.4	16.5
South Washington	13.0	11.2	12.9	12.4
North Oregon	14.1	16.3	21.7	17.4
South Oregon	10.5	13.5	17.5	13.8
California	15.8	19.5	16.4	17.2
mean	16.6	14.7	19.1	16.8

Figure 4.4a. Site x Origin interactions for LVVF% at 3.3 m height

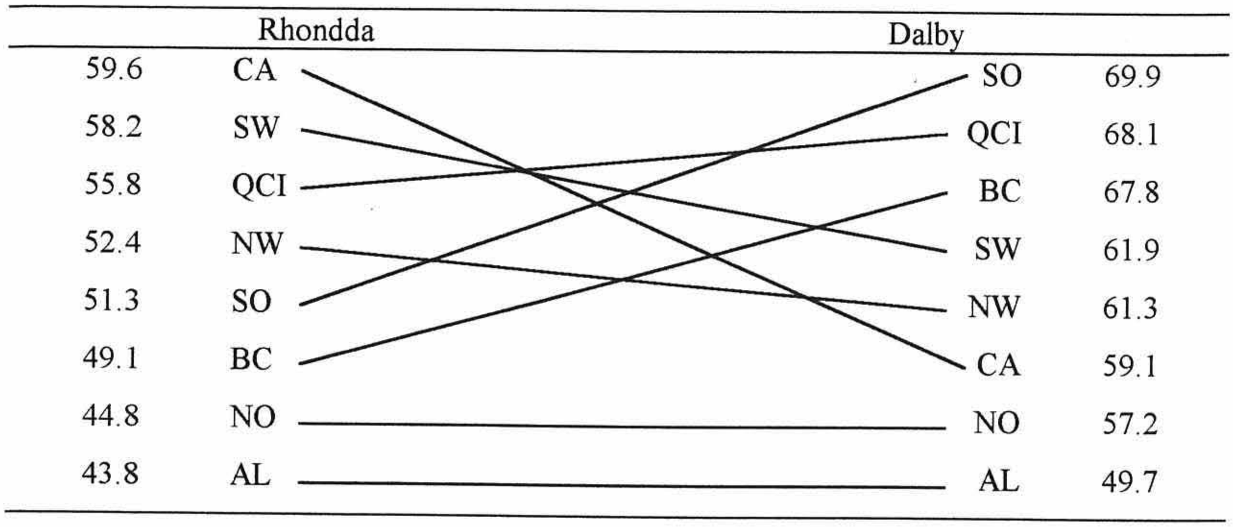


Figure 4.4b. Site x Origin interactions for LVVF% at 2.3 m height

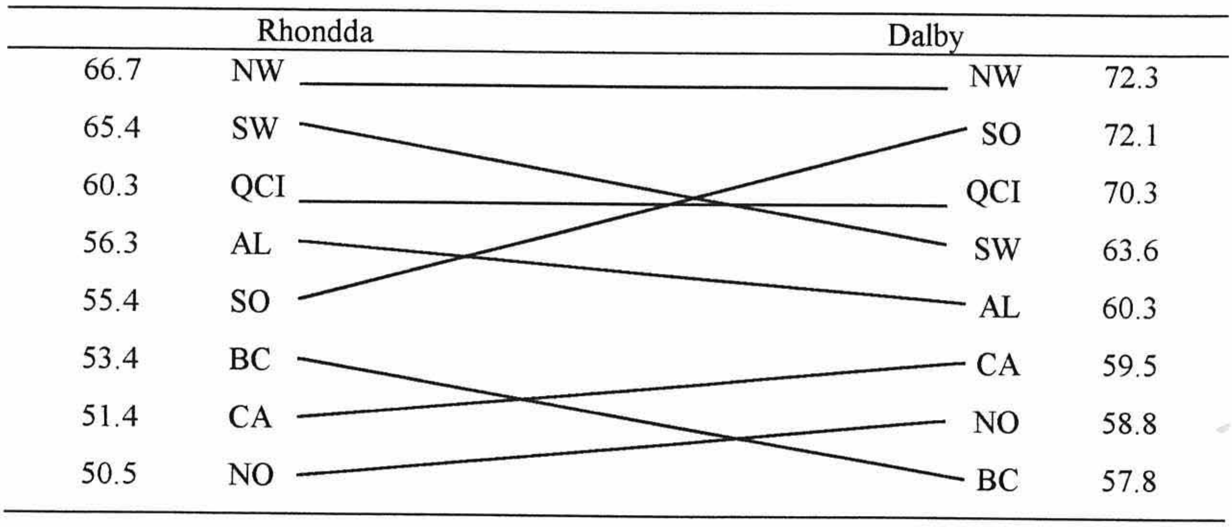


Figure 4.4c. Site x Origin interactions for LVVF% at 1.3 m height

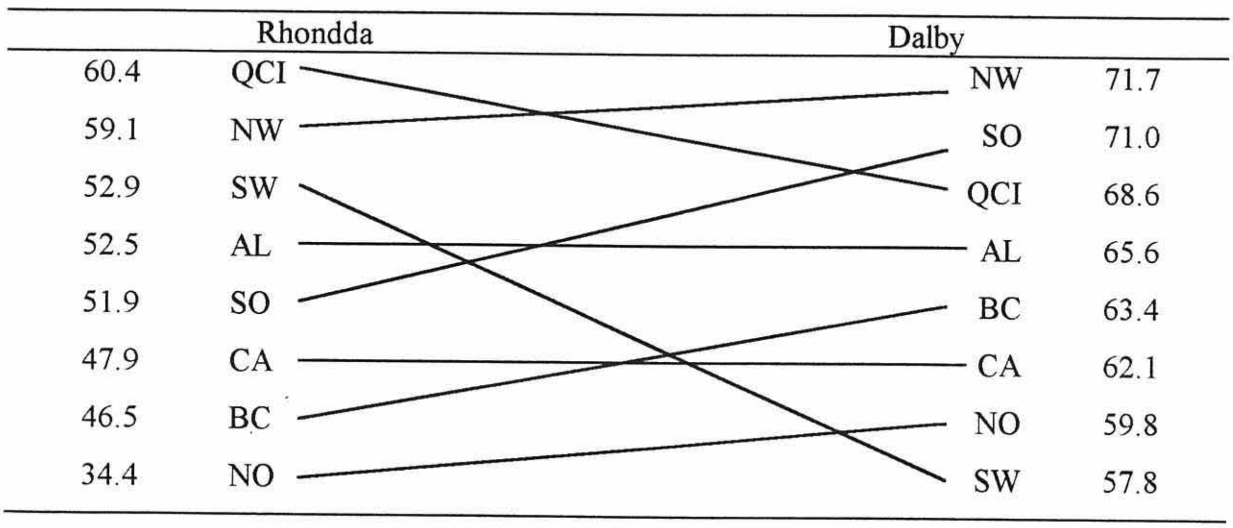


Figure 4.5a. Site x Origin interactions for RVVF% at 3.3 m height

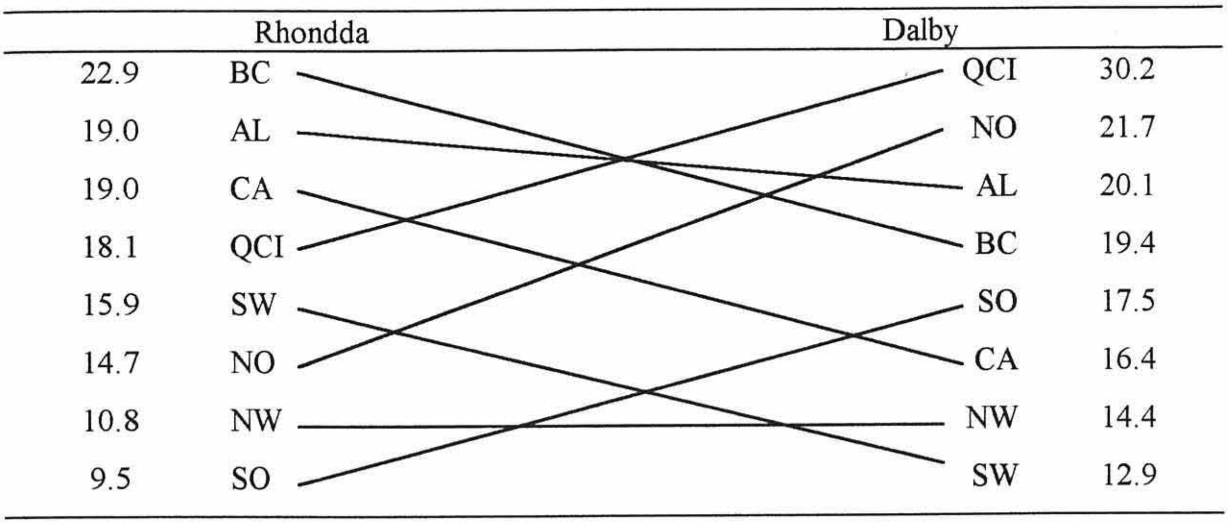


Figure 4.5b. Site x Origin interactions for RVVF% at 2.3 m height

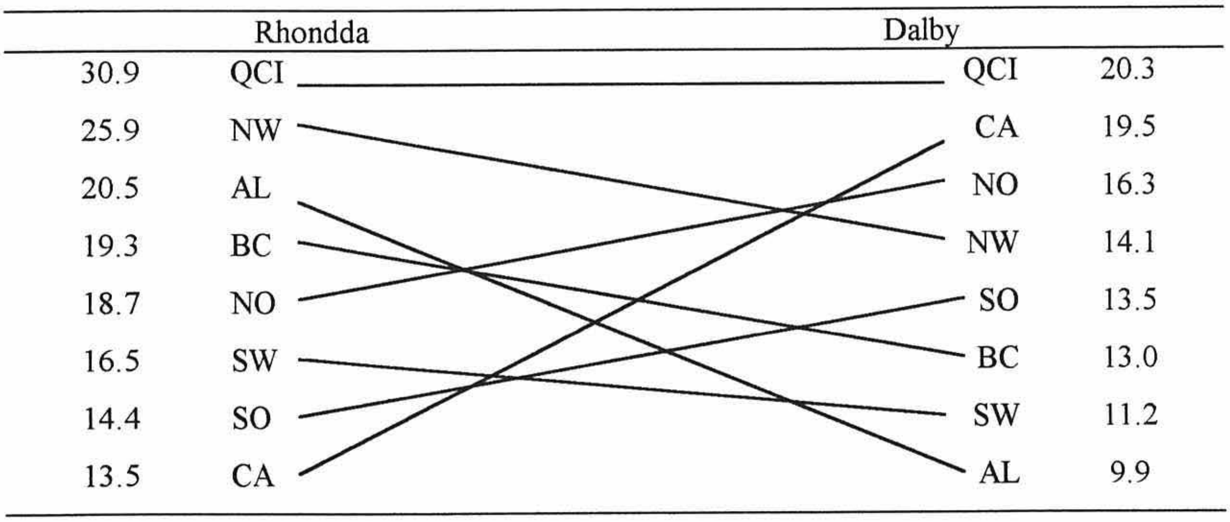
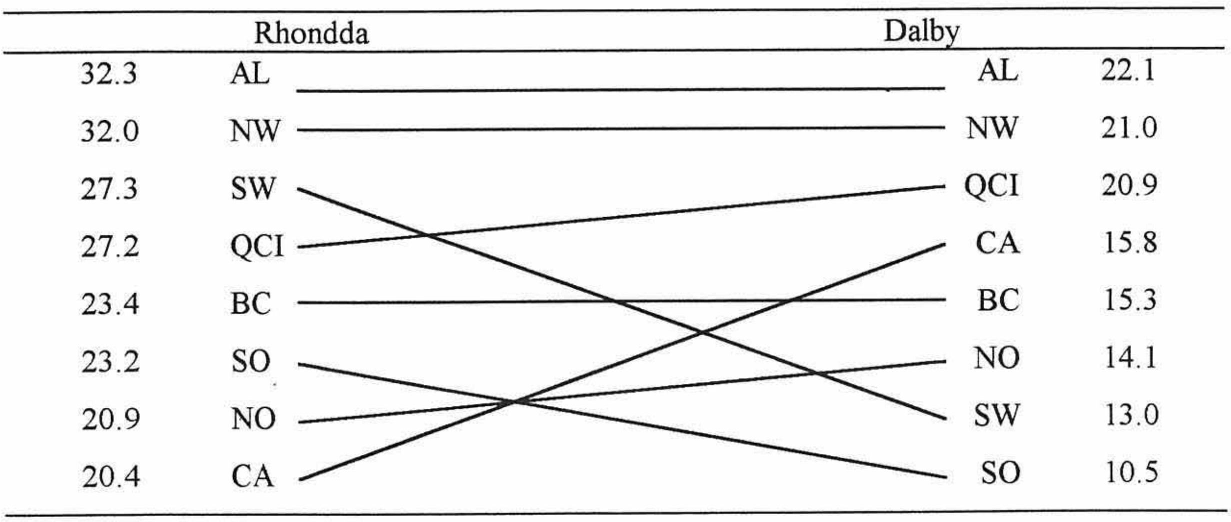


Figure 4.5c. Site x Origin interactions for RVVF% at 1.3 m height



4.5 Relationships between the Variables: Correlation Analysis

The relationships between the variables, diameter, density, ring width and the percentage of void volume filled in either longitudinal or radial flow directions, have been investigated by correlation analysis. Relationships of these at height (4.5.1), tree (4.5.2) and seed origin (4.5.3) levels have been examined.

The relationships between the considered variables are also shown in the scatter plots for overall means, Rhondda and Dalby at height, tree and seed origin levels (Appendix 2 and 3).

4.5.1 Relationships at the Height Level

Correlation analysis for height level for both sites (2 site x 8 seed origin x 5 tree x 3 sample) is shown in Table 4.8a as a matrix form, and for each site (8 seed origin x 5 tree x 3 sample) is given in Table 4.8b where the correlations between the variables are listed for site Rhondda in above diagonal, and for site Dalby in below diagonal.

According to overall means for height level, the correlation matrix showed that significant negative correlations were observed between density and both diameter and ring width, and also between ring width and the percentage of void volume filled in longitudinal flow direction (LVVF%). On the other hand, there were significant positive correlations between LVVF% and either diameter or density.

More of the correlations were significant with samples from Dalby than from Rhondda. In Rhondda (above the diagonal, Table 4.8b), there were negative correlations between ring width and density, while positive correlations between density and LVVF%. All the findings of Rhondda also occurred in Dalby (below the diagonal, Table 4.8b). In addition negative correlations were observed between diameter and density, and also between ring width and LVVF%. Furthermore, positive correlations were noted between diameter and both ring width and LVVF%.

Table 4.8a. The correlation matrix showing the correlations between the variables of the 240 experimental samples of both sites.

source	diameter	density	ring width	LVVF%
density	**-0.206**			
ring width	0.041	**-0.503**		
LVVF%	**0.245**	**0.197**	**-0.330**	
RVVF%	0.029	-0.004	0.094	0.015

• The critical value is 0.138 for overall means, and the significant correlations are indicated in bold.

Table 4.8b. The correlation matrix showing the correlations between the variables of the 120 experimental samples of each site.

source	diameter	density	ring width	LVVF%	RVVF%
diameter	-	-0.048	-0.057	0.070	0.191
density	**-0.309**	-	**-0.640**	**0.197**	0.031
ring width	**0.402**	**-0.582**	-	-0.162	-0.103
LVVF%	**0.226**	**0.303**	**-0.202**	-	0.189
RVVF%	-0.005	-0.071	0.119	0.011	-

• Correlations between the variables are given for Rhondda in above diagonal, for Dalby in below diagonal.
• The critical value is 0.195 for both sites, and the significant correlations are indicated in bold.

For the combined data of both sites (Table 4.9a) linear regressions between density and ring width (R^2 = 0.253) were much greater than those for density with diameter (R^2 = 0.042) although in either case the correlations are poor. Furthermore, such anatomical patterns showed different variation between the percentage of void volume filled in longitudinal flow direction (LVVF%). Linear regressions between LVVF% and tree diameter (R^2 = 0.060) were greater than that for LVVF% with density (R^2 = 0.039, Table 4.9a). However, the most important factor explaining higher longitudinal fluid uptake was the mean growth ring width (R^2 = 0.109).

Within the trees of the Rhondda site, the variations of the wider ring width which were quite uniform, and an identical pattern was recorded in Dalby with narrow but uniform ring width. As is shown in Table 4.9b and c ring width accounted for more of the variation in density of the wood than tree diameter in both sites. Linear regressions showed that ring width accounted for much more variation in density between trees in Rhondda (R^2 = 0.410) than in Dalby (R^2 = 0.339), whereas the tree diameter accounted for very little variation in Dalby (R^2 = 0.009) only.

Correspondingly, the rate of the increase in LVVF% reflected the rate of increase in the tree diameter ($R^2 = 0.051$) with decrease in ring width ($R^2 = 0.339$) in Dalby. This result has also been noticed in Rhondda, although the correlations were not statistically significant in that case.

Therefore, comparison of the two sites suggests that LVVF% was lowest at Rhondda which had the slowest growth rate (tree diameter) with highest density, and the LVVF% was greater at Dalby which had a higher growth rate but lower density. Consequently, the slower grown wood of the Rhondda trees had considerably lower LVVF% than that of the faster grown Dalby trees.

Table 4.9. Linear regression equations and coefficient of determinations between the measured variables at height level in (a) both the two trial sites, (b) Rhondda, (c) Dalby.

EQUATION			R^2
a) Rhondda and Dalby			
density	=	470 - 4.43 diameter	0.042
density	=	487 - 16 ring width	0.253
LVVF%	=	38.7 + 1.51 diameter	0.060
LVVF%	=	72.6 - 3.01 ring width	0.109
LVVF%	=	35.3 + 0.0564 density	0.039
b) Rhondda			
density	=	537 - 22.8 ring width	0.410
LVVF%	=	31.6 + 0.0524 density	0.039
c) Dalby			
density	=	497 - 6.51 diameter	0.096
density	=	491 - 20.8 ring width	0.339
LVVF%	=	46.7 + 1.24 diameter	0.051
LVVF%	=	71.3 - 1.89 ring width	0.162
LVVF%	=	31.4 + 0.0793 density	0.092

4.5.2 Relationships at the Tree Level

Correlation analysis at the tree level for both sites (2 site x 8 seed origin x 5 tree) is shown in Table 4.10a, and for each site (8 seed origin x 5 tree) in Table 4.10b where the correlations between the variables are given for Rhondda at the above diagonal, for Dalby at the below diagonal. The correlation matrix showed significant correlations between diameter, ring width and density. Significant correlations at the tree level were similarly observed as at the height level (4.5.1) that there were negative correlations between density and both diameter and ring width, and also between ring width and the percentage of void volume filled in longitudinal flow direction (LVVF%). There were positively significant correlations between LVVF% and both diameter and density.

The measured variables at the tree level were more significantly correlated to each other in Dalby than in Rhondda as with the height level. As is seen in Table 4.10b, in Rhondda (above the diagonal), there were negative correlations between density and ring width. In Dalby (below the diagonal) in addition to the findings in Rhondda, negative correlations were also observed between density and diameter. However, positive correlations occurred between diameter and ring width, density and LVVF%.

Table 4.10a. The correlation matrix showing the correlations between the measured variables at source of the mean data on all the 80 trees of both site.

source	diameter	density	ring width	LVVF%
density	**-0.390**			
ring width	**0.219**	**-0.522**		
LVVF%	**0.330**	**0.220**	**-0.388**	
RVVF%	-0.128	-0.051	0.201	-0.018

• The critical value is 0.217 for overall means, and the significant correlations are indicated in bold.

Table 4.10b. The correlation matrix showing the correlations between the measured variables at source of the mean data on all the 40 trees of each site.

source	diameter	density	ring width	LVVF%	RVVF%
diameter	-	-0.300	0.199	0.189	-0.225
density	**-0.448**	-	**-0.711**	0.253	-0.049
ring width	**0.653**	**-0.617**	-	-0.174	0.012
LVVF%	0.228	**0.334**	-0.228	-	0.221
RVVF%	0.060	-0.105	0.108	0.067	-

• Correlations between the variables are given for Rhondda in above diagonal, for Dalby in below diagonal.
• The critical value is 0.304 for both sites, and the significant correlations are indicated in bold.

Table 4.11a shows linear regression equations and coefficient of determinations for mean density with diameter and ring width between trees of all sites. Density was inversely correlated with diameter (R^2 = 0.152) but between tree differences in density were most closely associated with ring width which accounted for more variation in density (R^2 = 0.273). In the same way, the linear regression between LVVF% and ring width (R^2 = 0.151) was closer than that for LVVF% with diameter (R^2 = 0.109).

The correlations between density and ring width were greater at Rhondda than at Dalby. In Dalby there were also significant correlations between density and diameter (R^2 = 0.201). Between the trees within the Rhondda site showed that density was associated with ring width (R^2 = 0.505). In Dalby, ring width (R^2 = 0.380) again accounted for more of the variation in density. Considering between tree variations within each site, there were no significant differences in LVVF% between the forty trees sampled from the eight seed origins at Rhondda (Table 4.11b). At Dalby however, there were positive and significant correlations between LVVF% and density (R^2 = 0.111).

Table 4.11. Linear regression equations and coefficient of determinations between the measured variables at tree level in (a) both the two trial sites, (b) Rhondda, and (c) Dalby.

EQUATION			R^2
a) Rhondda and Dalby			
density	=	539 - 9.64 diameter	0.152
density	=	493 - 17.3 ring width	0.273
LVVF%	=	30.3 + 2.15 diameter	0.109
LVVF%	=	74.4 - 3.4 ring width	0.151
LVVF%	=	34.6 + 0.0582 density	0.049
b) Rhondda			
density	=	563 - 27.7 ring width	0.505
c) Dalby			
density	=	543 - 9.82 diameter	0.201
density	=	501 - 23.3 ring width	0.380
LVVF%	=	31.2 + 0.0797 density	0.111

4.3.3 Relationships at the Seed Origin Level

Correlation analysis at seed origin level for both sites (2 site x 8 seed origin) is shown in Table 4.12a, and for each site (8 seed origin) in Table 4.12b where the correlations between the variables is listed for Rhondda at the above diagonal, for Dalby at the below diagonal. The correlation matrix at the seed origin level on overall means of both sites showed no significant correlations between any of the variables. However, the correlations were higher when sites were considered separately.

As seen in Table 4.12b, in Rhondda (above the diagonal), there were negative correlations between ring width and density. In Dalby (below the diagonal) in addition of the findings in Rhondda, the correlations were also observed negatively between diameter and density.

Table 4.12a. The correlation matrix showing the correlations between the measured variables at source of the mean data on all the 8 seed origins of both site.

source	diameter	density	ring width	LVVF%
density	-0.579			
ring width	0.073	-0.580		
LVVF%	0.507	-0.038	-0.598	
RVVF%	-0.112	0.003	0.381	-0.214

• The critical value is 0.666 for overall means, and the significant correlations are indicated in bold.

Table 4.12b. The correlation matrix showing the correlations between the measured variables at source of the mean data on all the 8 seed origins of each site.

source	diameter	density	ring width	LVVF%	RVVF%
diameter	-	-0.315	0.374	-0.026	-0.420
density	**-0.812**	-	**-0.897**	0.372	-0.140
ring width	0.637	**-0.807**	-	-0.454	0.007
LVVF%	0.453	-0.259	-0.101	-	0.393
RVVF%	0.463	-0.019	0.169	0.156	-

• Correlations between the variables are given for Rhondda in above diagonal, for Dalby in below diagonal.
• The critical value is 0.666 for both sites, and the significant correlations are indicated in bold.

At the seed origin level (Table 4.12a), density was associated with ring width and diameter, although the correlations were not statistically significant. At each site however, ring width were significantly correlated with density (Table 4.13b and c). Density was more inversely associated with ring width in Dalby (R^2 = 0.804) than in Rhondda (R^2 = 0.781). The significant correlations between seed origin differences also occurred between density and diameter but only in Dalby (R^2 = 0.099).

Table 4.13. Linear regression equations and coefficient of determinations between the measured variables at origin level in (a) Rhondda, and (b) Dalby.

EQUATION			R^2
a) Rhondda			
density	=	528 - 24.9 ring width	0.781
b) Dalby			
density	=	602 - 14.8 diameter	0.099
density	=	580 - 30.8 ring width	0.804

5 DISCUSSION

Tree improvement of Sitka spruce is a combination of silviculture and tree breeding aimed at producing higher quality products including increased growth rate and timber yield (Fletcher, 1992), and wood density (Denne and Dodd, 1980). It is useful to know annual ring structure and density distribution when studying the quality of wood, grading it, or determining how the wood structure affects residual flow in softwoods (Clauson and Wilson, 1991). Softwood structure, for example, may have a high proportion of earlywood the pits of which aspirate on drying.

Wood density of Sitka spruce varies considerably with distance from the pith, with height in the tree, between trees and with silvicultural management and site class (Broughton, 1962; Brazier, 1972; Bendtsen, 1978; Denne, 1979; Denne and Dodd, 1980; Dinwoodie, 1981; Delobrate, 1984; Harding, 1988; Murphy and Pfeifer, 1990; Mitchell, 1995; Simpson and Denne, 1997). These density variations have also been shown to influence critical strength properties, including breaking strength, elasticity and shrinkage (Brunden, 1964; Fielding, 1967; Harris, 1969; Bendtsen, 1978; Walker, 1984), and have also been indicated for effects on permeability (Kollmann and Cote, 1968; Koch, 1972; Siau, 1971; Nicholas and Siau, 1973; McQuire, 1975; Taylor, 1991; Eaton and Hale, 1993).

Therefore, this study has demonstrated within and between tree variations in wood characteristics which importantly influence the density and permeability from various seed origins grown at an eastern (Dalby, England) and a western (Rhondda, Wales) UK sites.

In this chapter, the results in both density and permeability trials have been presented according to variations within and between trees and also between seed origins with both overall means and means of each site.

5.1 Density

5.1.1 Within Tree Variation

Horizontal Variation

In this study, the vertical variation in wood density of Sitka spruce has been analysed from the base to top of the tree rather than horizontal variation (from pith to bark) because the experimental plug samples, which were used for both the permeability trials and density measurements, were taken from only the outer growth rings of the selected discs.

Since tracheids account for about 90% of the wood volume in softwood (Scaramuzzi, 1965 Sjöström, 1993) density is likely to depend on both the diameter and wall thickness of the tracheids (Wilcox, 1973; Denne, 1979; Lewark, 1986; Thompson, 1992;) and on the proportions of latewood to earlywood (Wilson and White, 1986). It has been reported that latewood percentage (Harris, 1971) and also mean wall thickness of latewood tracheids (Schultze-Dewitz, 1965) increase with cambial age (distance from the pith), thus increasing the density of the mature wood (Pearson and Gilmore, 1980; Megraw, 1985; Fries, 1986).

Without a full analysis of the horizontal variation from pith to bark, as mentioned by Dinwoodie (1981) and Tsoumis (1991), it is not possible to fully comment on horizontal variation. However, density tended to decrease with increasing growth rate (ring width).

The horizontal variation in density is attributed to the influence of cambial growth rate as shown by ring width (Brazier, 1967), and is mainly due to combined effect of the number of tracheids per unit area and latewood percentage (Olesen, 1977). In consequence therefore, wood density tended to decrease in trees with growth rings which had a lower amount of the latewood (i.e. those at Dalby).

As mentioned by Brazier (1972), Bumber and Burley (1983) and Delobrate (1984), the lower density was accompanied by increased mean ring width with larger tree diameter.

Consequently, the slower grown wood of the Rhondda trees had higher density than that of the faster grown Dalby trees where the diameter was also directly related to density.

Vertical Variation

The overall trends of the vertical variation in wood density within trees that have been observed in the analyses, were also consistent with those established for spruces by previous workers (Brazier, 1970; Denne, 1979; Harvald and Oleson, 1987; Simpson, 1993; Mitchell, 1995). For a comparable number of rings in each sample tree, the density in mature wood of Sitka spruce was found to be slightly greater at breast (1.3 m) height than higher in the tree (corresponding to the trend noted by Harvald and Oleson, 1987), and this difference became more noticeable with increasing distance from breast height (Figure 5.1). In the work by Harvald and Oleson (1987) this was associated with significantly thicker tracheid walls and to a lesser extent, narrower radial and tangential tracheid diameters at breast height.

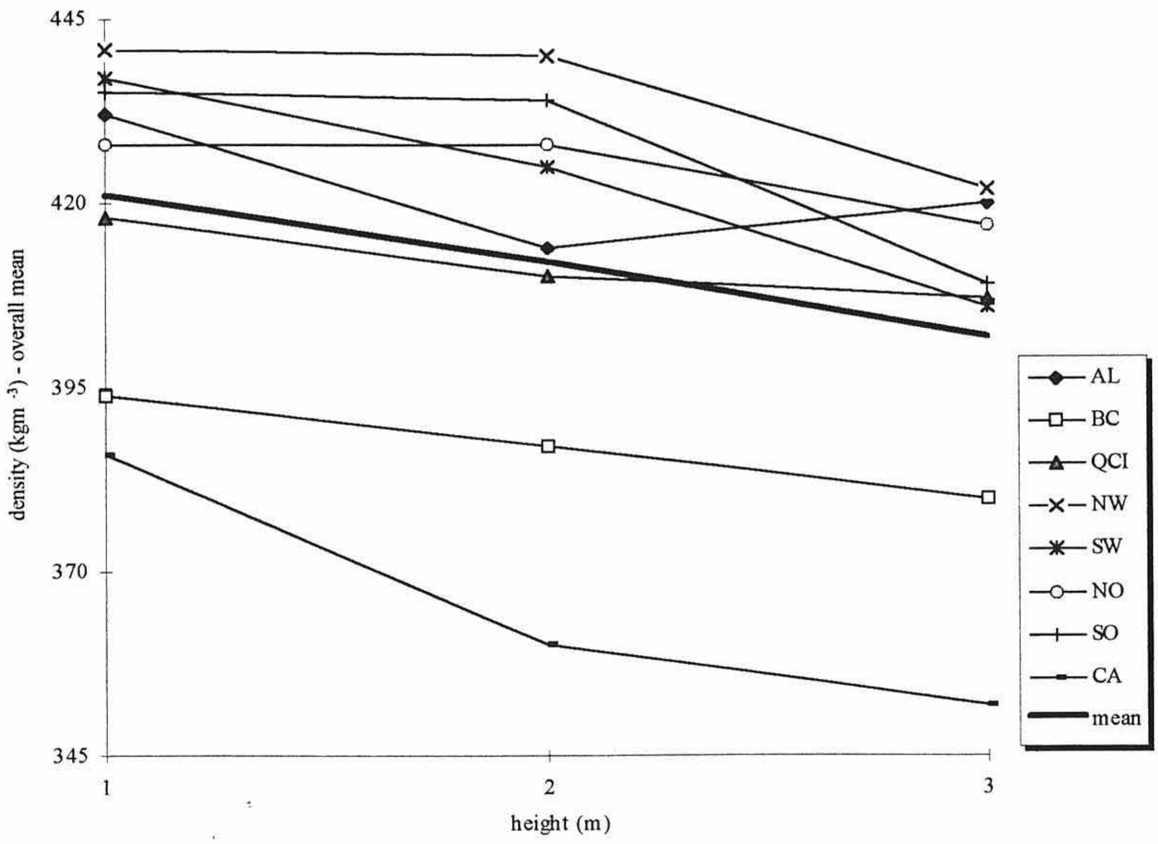


Figure 5.1. The vertical variation of density in each seed origin on overall means.

Comparing the results of density at the different heights (1.3, 2.3 and 3.3 m), it appears that density declines with increasing height in stem corresponding to a trend of increasing ring width from base to apex of the tree (Table 4.4a, 10a, Figure 5.2 and 5.3), and since these trends were common to all trees in both sites, such changes with height in a tree may perhaps be attributed to an effect of shoot apex ageing upon the progress of cambial ageing inherent to tree diameter growth (Mitchell and Denne, 1997).

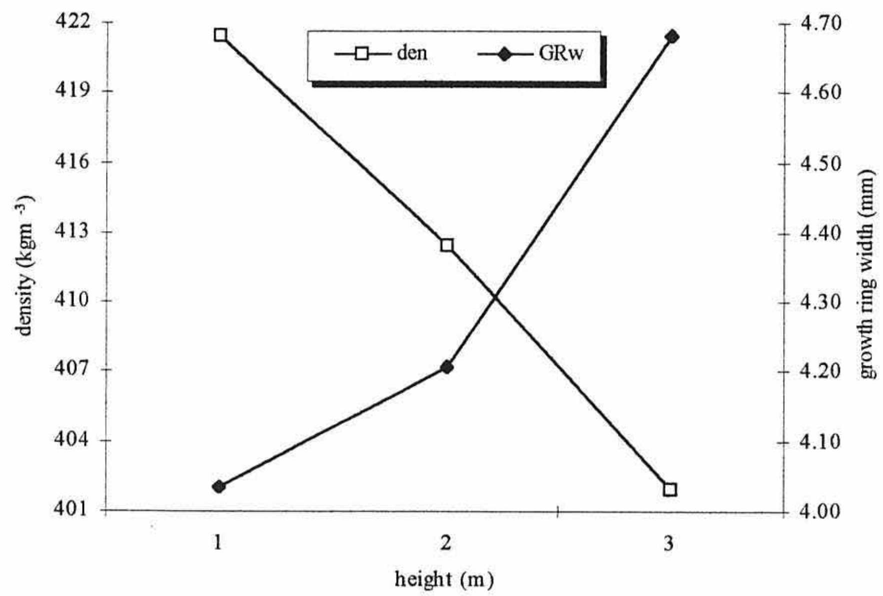


Figure 5.2. Comparison of changes of density and growth ring width on overall means.

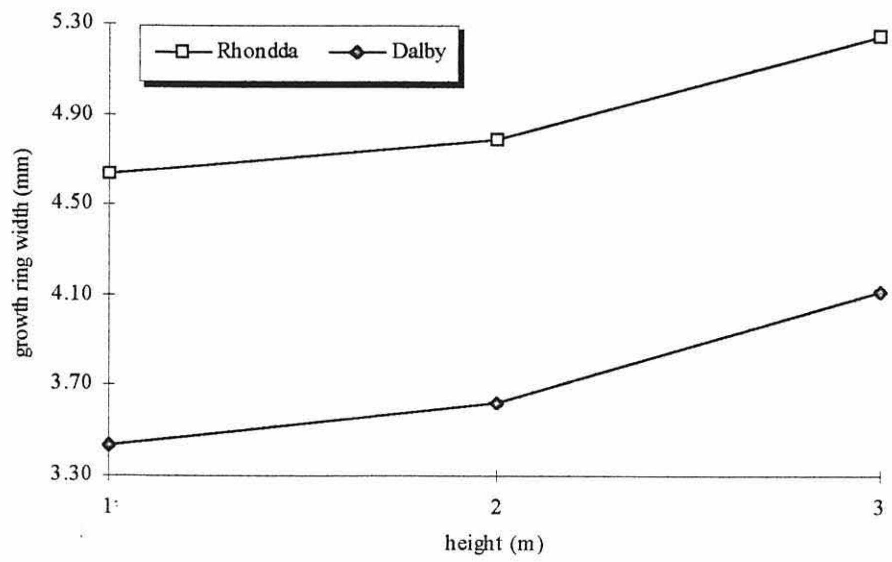
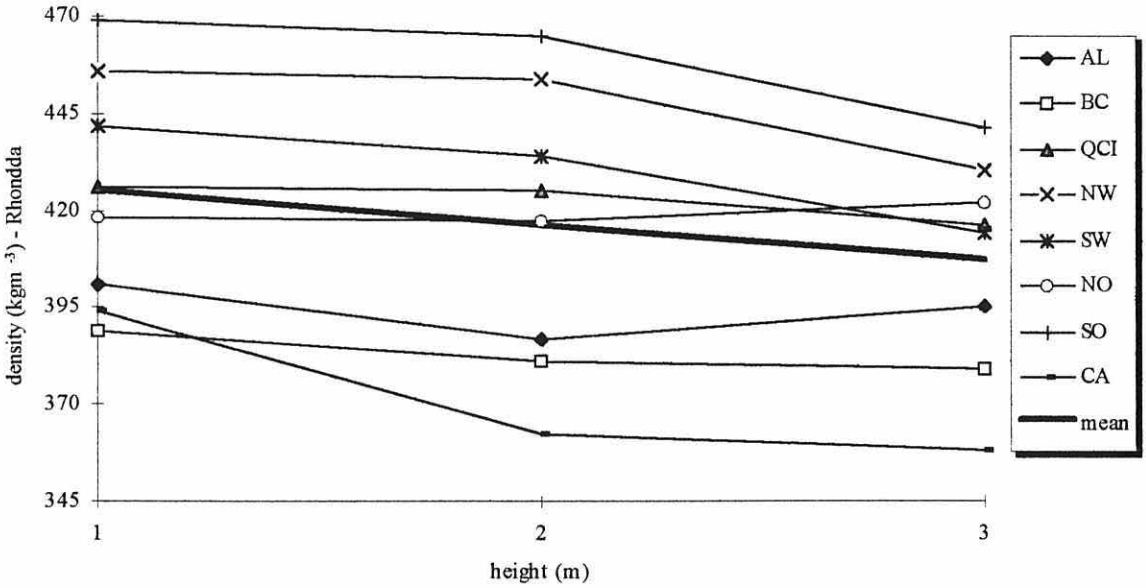


Figure 5.3. Vertical variation of growth ring width in both trial sites.

Between sites (Figure 5.4), there were also differences up the tree in the rate of decline in density and increase of ring width. This appeared to be related to the decrease in latewood proportion and was most marked in Rhondda. The wood density also showed systematic patterns of decrease with increasing tree height in both of the two sites. This would seem to suggest therefore that influences of tree growing conditions were superimposed upon the inherent changes associated with cambial age (Simpson, 1993; Mitchell, 1995).

(a) Rhondda



(b) Dalby

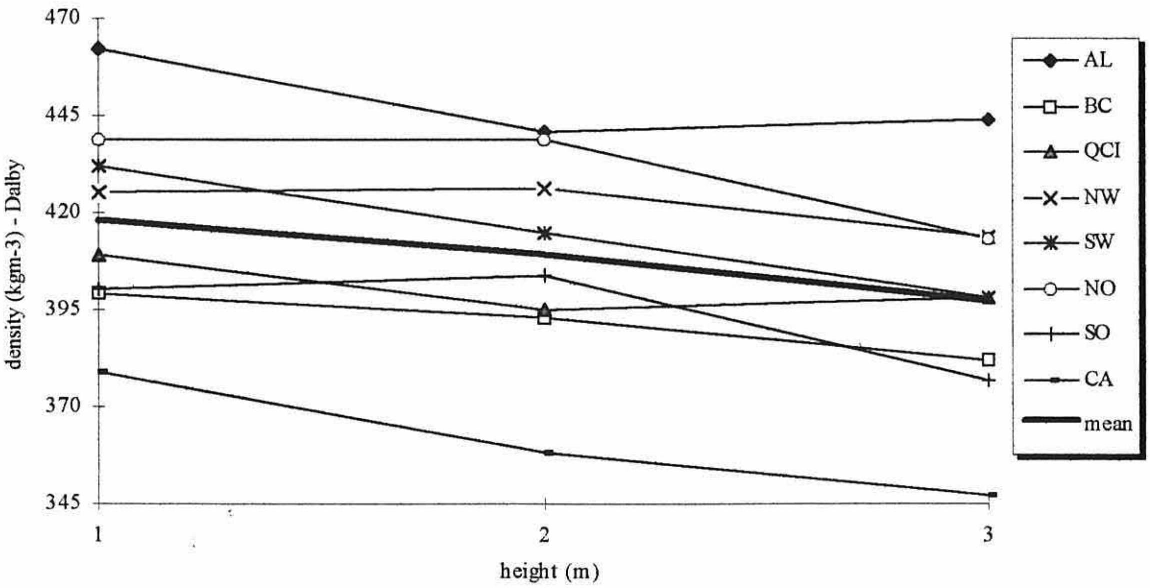


Figure 5.4. Vertical variation of density in each seed origin in (a) Rhondda and (b) Dalby.

As has been noted by Harvald and Oleson (1987) and Saranpaa (1994), density usually decreases with height in Sitka spruce. This was true in all the seed origins except the trees of AL and NO in Rhondda and AL, QCI, NW and SO in Dalby. In general, there was a minor increase in density between base and the centre of the trees in both NW and SO in Dalby, and between the centre and the top of the trees for the remainder seed origins (Table 4.4a, Figure 5.4). This case were also found by Spurr and Hsiung (1954) in spruce.

5.1.2 Between Tree Variation

For a single species density varies not only within trees (intratree) but also from tree to tree (intertree) (Kandeel and Bensend, 1969), those are the major sources of variability in wood quality (Panshin and de Zeeuw, 1980; Zobel and van Bujitenen, 1980; Wilson and White, 1986) which can be controlled by genetic and silvicultural means (Denne and Dodd, 1980).

In many previous investigations of Sitka spruce, mean tree density tends to be inversely correlated with the growth rate of the tree (Brazier, 1967; Denne, 1979; Harvald and Oleson, 1987; Maun, 1992; Simpson, 1993; Mitchell, 1995). Mitchell and Denne (1997) however suggested that density was less closely correlated with ring width than with tracheid dimensions. They showed that the variation in mean ring width which accounted for 30 %, and radial tracheid diameter plus wall thickness 66 % of the variation in mean tree density. Likewise, linear regressions between the present trees showed that density in Sitka spruce was less correlated with ring width (accounting for only 27.3 % of the variation, Table 4.11a). This is probably because ring width depends upon tracheid number as well as tracheid diameter, and those two parameters may to some extent be independent (Mitchell and Denne, 1997). It has also been found that wood density was more correlated with ring width in Rhondda than in Dalby accounting for 50.5 % and 38.0 % respectively (Table 4.11a and b). Tree diameter (20.1 %) also accounted for a little variation in density between trees of Dalby.

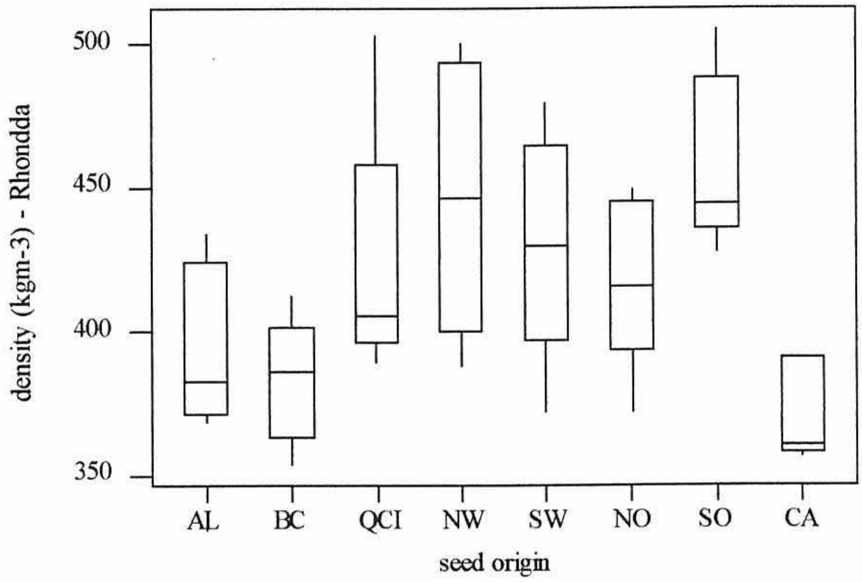
Since between tree differences in ring width may be due to either genetic or environmental influences on growth rate, it is difficult to distinguish genetic and environmental influences on density between trees (Mitchell and Denne, 1997). Within each site however, comparisons between trees which differ in density but have a similar growth rate should indicate parameters associated with genetic differences independent of environment (Brazier, 1967; Mitchell, 1995). Thus for example, trees of NW, SW and NO in both sites, SO in Rhondda, AL in Dalby had higher than average mean densities, and trees of BC and CA in both sites, AL in Rhondda, QCI and SO in Dalby had a lower than average density. However, trees of NW and SO in Rhondda, and AL and NO in Dalby had lower than average growth rates for their sites (Table 4.1b and c, and Figure 5.5). These results confirm earlier reports by Broughton (1962), Brazier (1972) and Murphy and Pfeifer (1990) who stated that there was an inverse correlation between wood density and tree volume. Therefore, it can be stated that the trees of NW and SO in Rhondda, AL and NO in Dalby had the highest wood density due partly to their slower rates of growth, and CA in both sites had the lowest density on account of its rapid growth.

Since between tree differences in density can be associated either with wall thickness or with differences in both wall thickness and radial tracheid diameter (Simpson, 1993; Mitchell, 1995), results from the trial trees indicate that it should prove feasible to improve density by selection for either thicker walled or narrower tracheids (Mitchell and Denne, 1997). Therefore, the narrower tracheids have been seen in the seed origins of QCI, NW, SW and NO in both sites, and SO in Rhondda, in either of these seed origins the wood density was also found higher among the other seed origins.

According to Thompson (1992) a longer growing season would increase the latewood proportion due to an increase of mean wall thickness of latewood tracheids. This would result in an increased density. Conversely a vigorous growth rate would generally result in a larger proportion of earlywood with larger lumens and result in a lower density. However, the trees of both AL and QCI in Dalby indicated different characteristics with having narrow (AL) and wider (QCI) tree diameter but greater density. This was probably because of the environmental influences on their growth rate.

According to Briand *et al.* (1993), radial tracheid diameters across wide growth rings are not only larger but also more constant in size for most of the ring (the plateau phase) before declining sharply at the latewood, and in less vigorous trees (having narrow rings) radial

(a) Rhondda



(b) Dalby

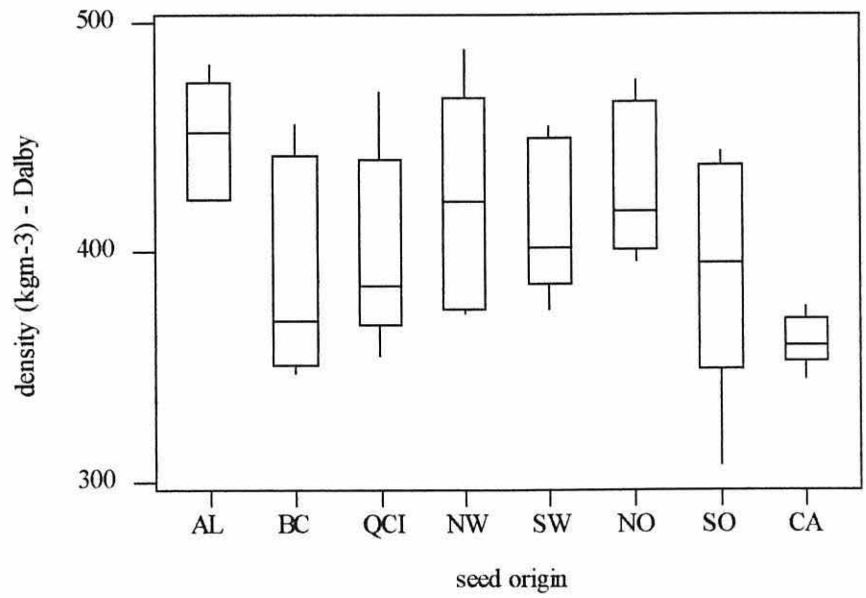


Figure 5.5. Boxplot[1] showing the density distribution of trees of each seed origin in trial sites (a) Rhondda, and (b) Dalby.

---

[1] Boxplot is also called as the box and whisker plot. The box shows the distance between the quartiles, with the median marked as a line, and the whiskers show the extremes (Bland, 1995).

tracheid diameter in earlywood has been reported to be smaller and the plateau phase much shorter or absent and there being a gradual decline to latewood. These trends usually result therefore, in an inverse relation between growth rate and density, and so breeding programmes which are currently producing trees of faster growth with small diameter branches, may consequently tend to produce trees of reduced density (Maun, 1992).

Thompson (1992) indicated that increased vigour does not automatically result in lower density and this suggests a great genetic potential for selecting vigorous trees with acceptable density values. Thus, the trees of QCI, NW, SW and NO may be identified as favourable genotypes to produce wood of adequate density under the UK conditions tested.

5.1.3 Between Seed Origin Variation

Differences in wood density between seed origins grown on the same site are also dependent on the site conditions that control to the growth rate of the seed origins as a result of the properties of the soil (fertility, depth, moisture retention) and the climate (temperature, photoperiod, light intensity, rainfall) which are both significantly affected by altitude (Larson, 1969). For example, it has been demonstrated by Chalk (1951) that latewood formation and therefore density is affected by moisture availability through either soil retention or regular precipitation, i.e. latewood proportion generally tends to increase with increasing water availability during the period of latewood formation.

The variation in density between the seed origins was confined to the outer rings which in the Dalby trees were significantly narrower probably due to increased competition between the trees. However, the density of these outer rings was significantly higher in the Rhondda trees. Between the seed origins on these two sites, significant differences were evident in ring width which is greater in Rhondda than in Dalby probably as a result of a higher rainfall in Rhondda (2400 mm/year) compared to that for Dalby (835 mm/year).

As mentioned by Fletcher (1992), the results of IUFRO seed collection experiments in 1969/70 have indicated that there were differences between seed origins in growth rates, phenology and wood properties and that by selecting the correct seed origin gains can be achieved. The QCI origins were good general purpose sources which were reasonably frost hardy, resistant to exposure and produce acceptable timber. On less exposed, more favourable sites, especially in south-west England, Wales and parts of west Scotland, origins from Washington and on some sites Oregon could be used with increases in timber production but with the possibility of a slight decrease in strength properties.

The trees originating from CA and SO (Dalby) were found to grow much faster than would be expected from their latitude of origin, while those from BC (Dalby) were much less vigorous than would be expected (Table 4.1c). Further, as it was initially shown by Lines (1987), it was also found in this study that seed origin AL and BC grew poorly in both sites, it may be therefore suggested that these two seed origins should be avoided in the future plantations. However, QCI, NW, SW and NO should be selected for more plantations as all grow well with a good density (Figure 5.6). On the other hand, CA in both sites, and SO in Dalby showed the fastest growth but low density. It should be possible to select for individuals with high volume (growth rate) production but without a corresponding decrease in density because the considerable gains in growth rate can be achieved at the expense of a slight decrease in wood density (Fletcher, 1992). From the results of this study, a typical example of this is QCI.

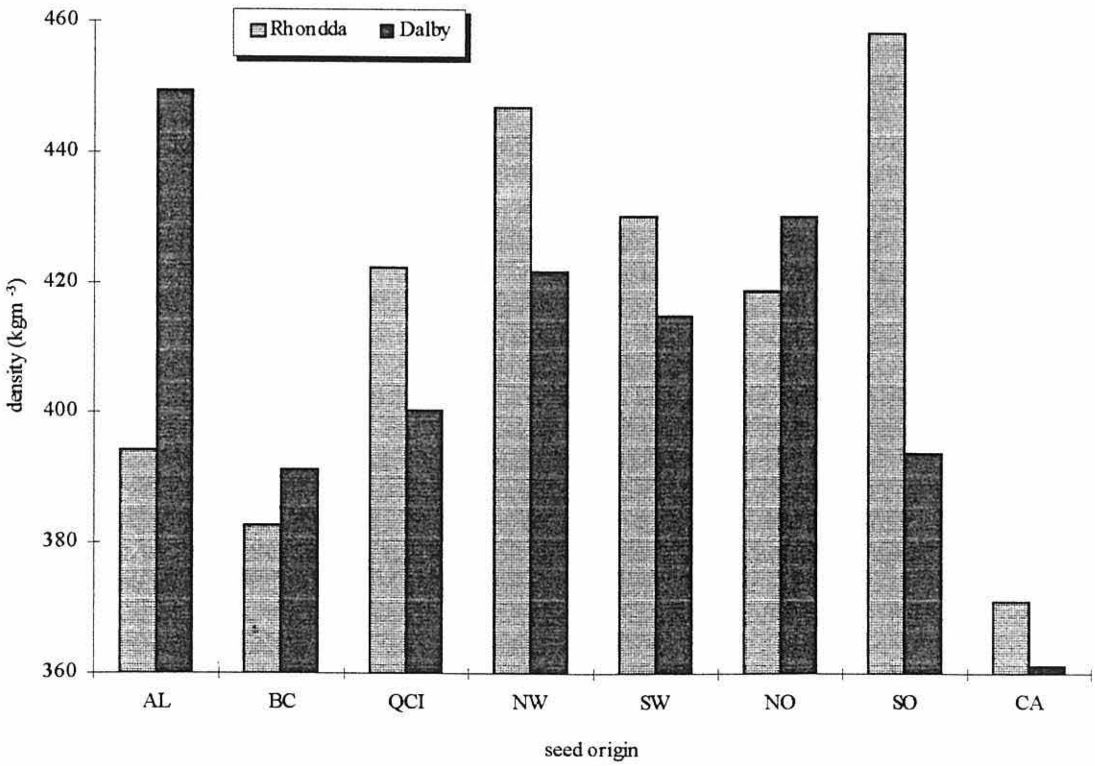


Figure 5.6. The variation of density between seed origins in Rhondda and Dalby.

5.2 Permeability

5.2.1 Within Tree Variation

The LVVF% increased from the base (1.3 m) to the centre (2.3 m) but decreased from 2.3 m height to the top (3.3 m) of the tree (Table 4.6a, Figure 5.7, 5.8a). On the other hand, RVVF% had an inverse relationship to LVVF%, i.e. there was a decrease trend from the base to the centre (2.3 m), and an increase trend from 2.3 m height to the top of the tree (Table 4.6b, Figure 5.7, 5.8b). Generally, it shows that either the highest LVVF% or the lowest RVVF% occurred in the centre height of the tree (Figure 5.7).

Comparison of overall means of both LVVF% and RVVF%, which are shown in Figure 5.7a and b, suggest that longitudinal permeabilities (LVVF%) were almost the mirror image of those for the radial permeability (RVVF%) along the tree trunk (Figure 5.7). QCI however showed combinations of both, i.e. LVVF% and RVVF% maintained high (65.3, 25.6) at the centre height of the tree, and low (61.9, 24.1) at the top height (Figure 5.8).

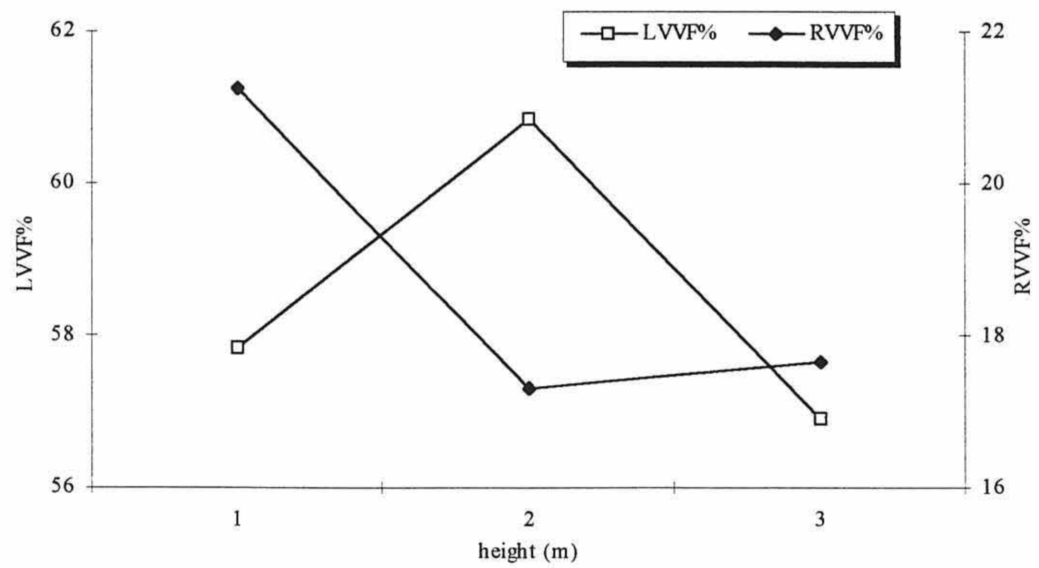
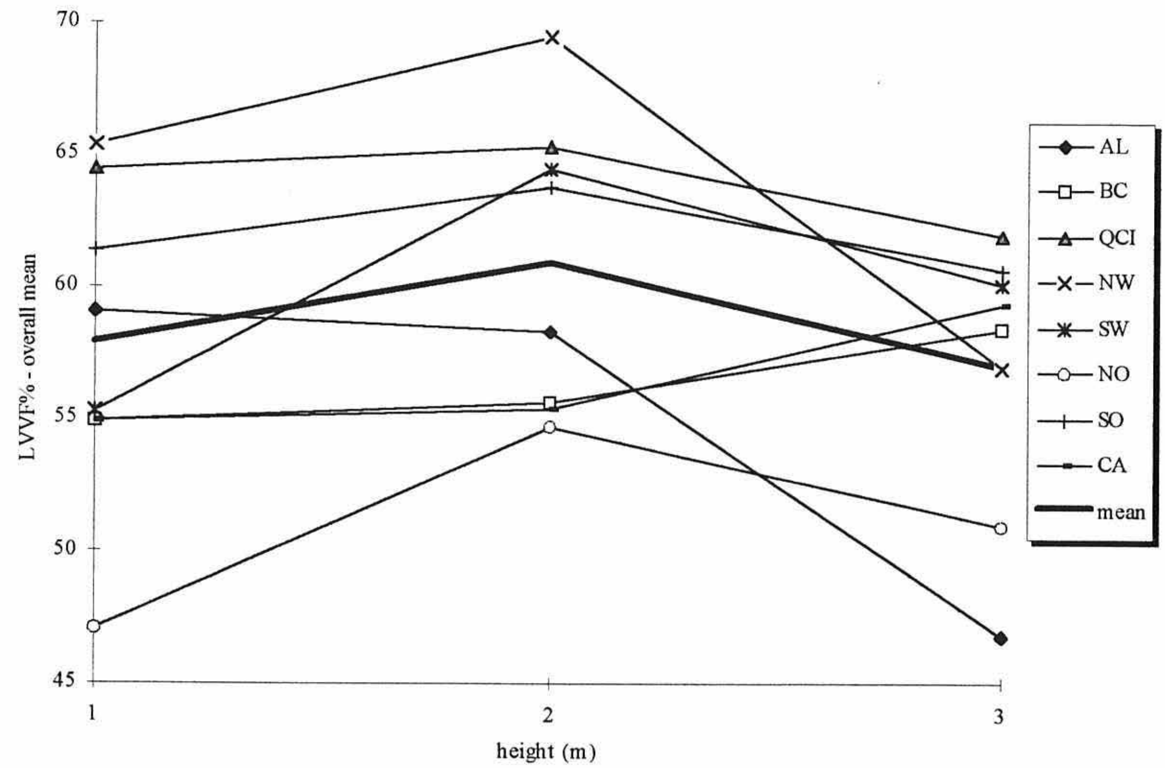


Figure 5.7. Comparison of changes of LVVF% and RVVF% within the tree.

Comparing the sites, it also appeared that there were an inverse relation between the LVVF% and RVVF% at all the three heights from base to apex of the tree, although the overall variation in LVVF% and RVVF% were greater in the seed origins growth in Rhondda (Figure 5.9 and 5.10).

(a) LVVF%



(b) RVVF%

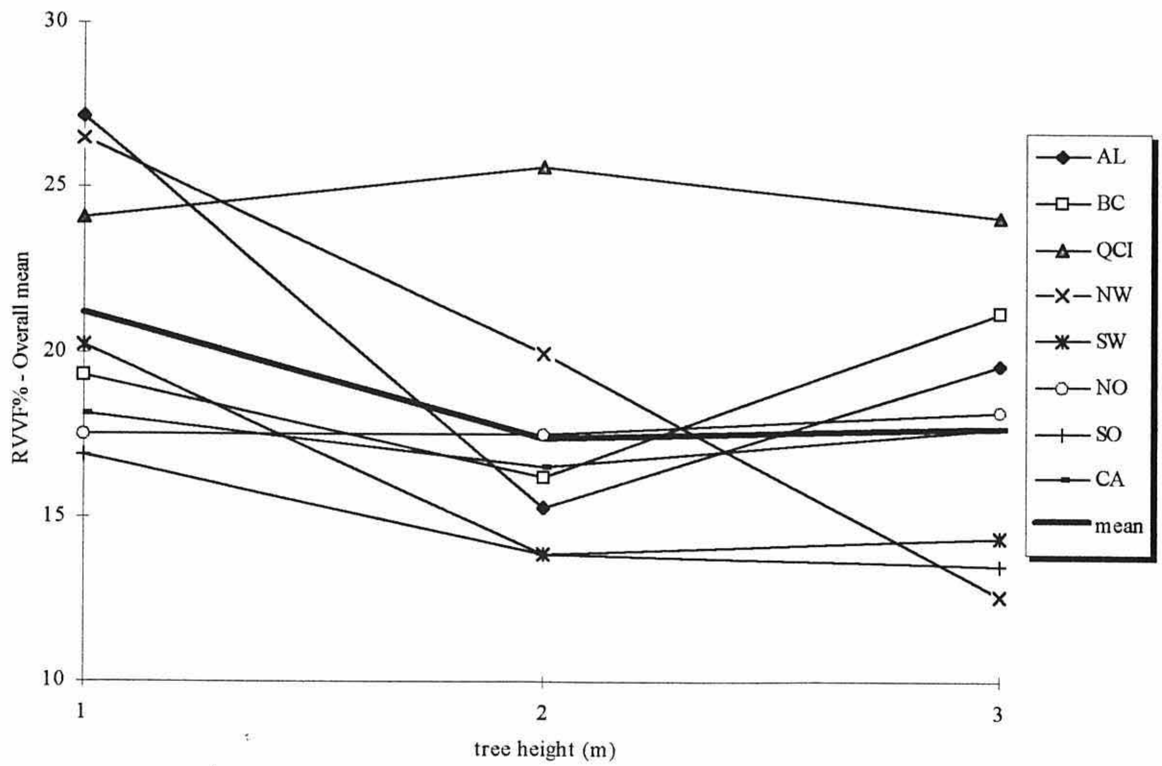
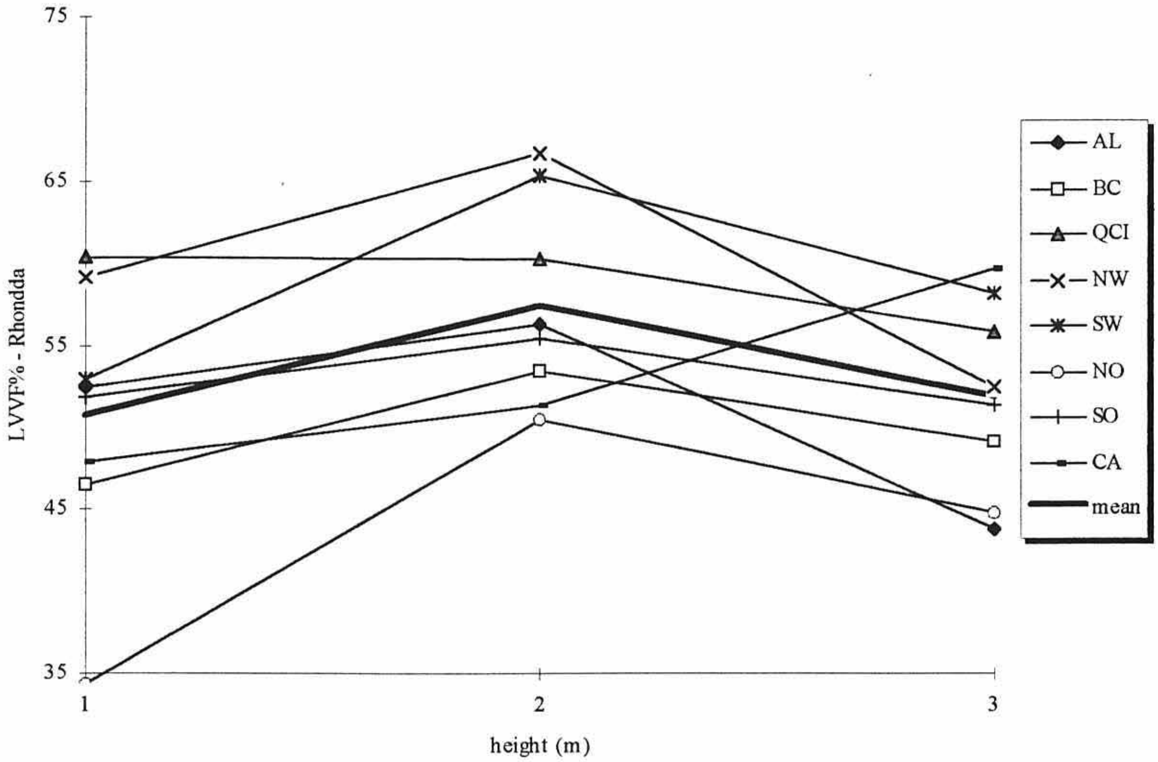


Figure 5.8. Vertical variation of both (a) LVVF% and (b) RVVF% within trees.

(a) LVVF% - Rhondda



(b) LVVF% - Dalby

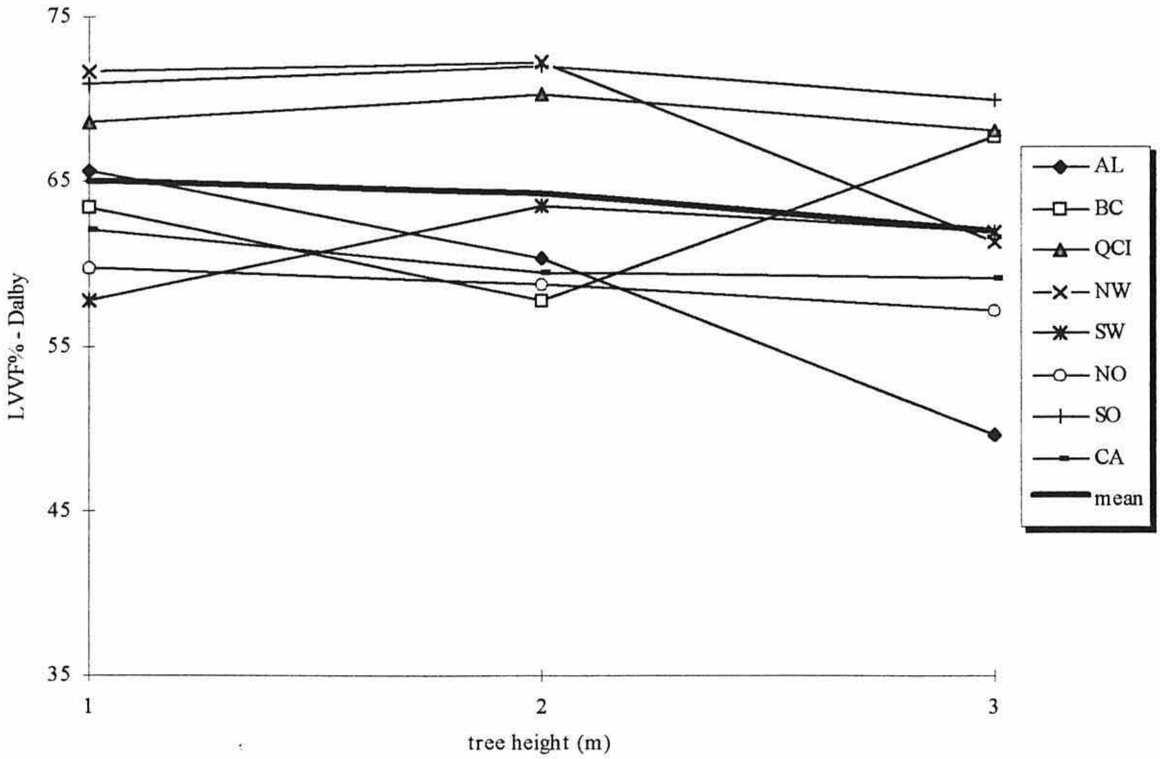
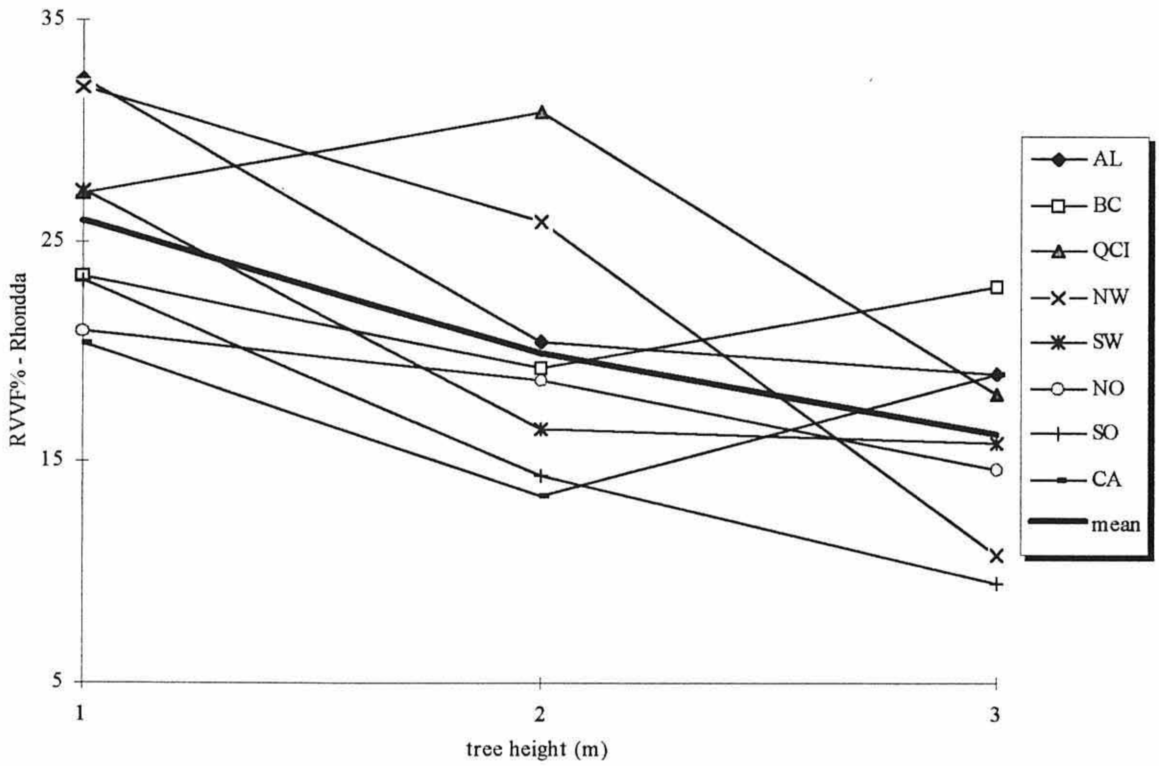


Figure 5.9. Vertical variation of LVVF% in (a) Rhondda and (b) Dalby within trees.

(a) RVVF% - Rhondda



(b) RVVF% - Dalby

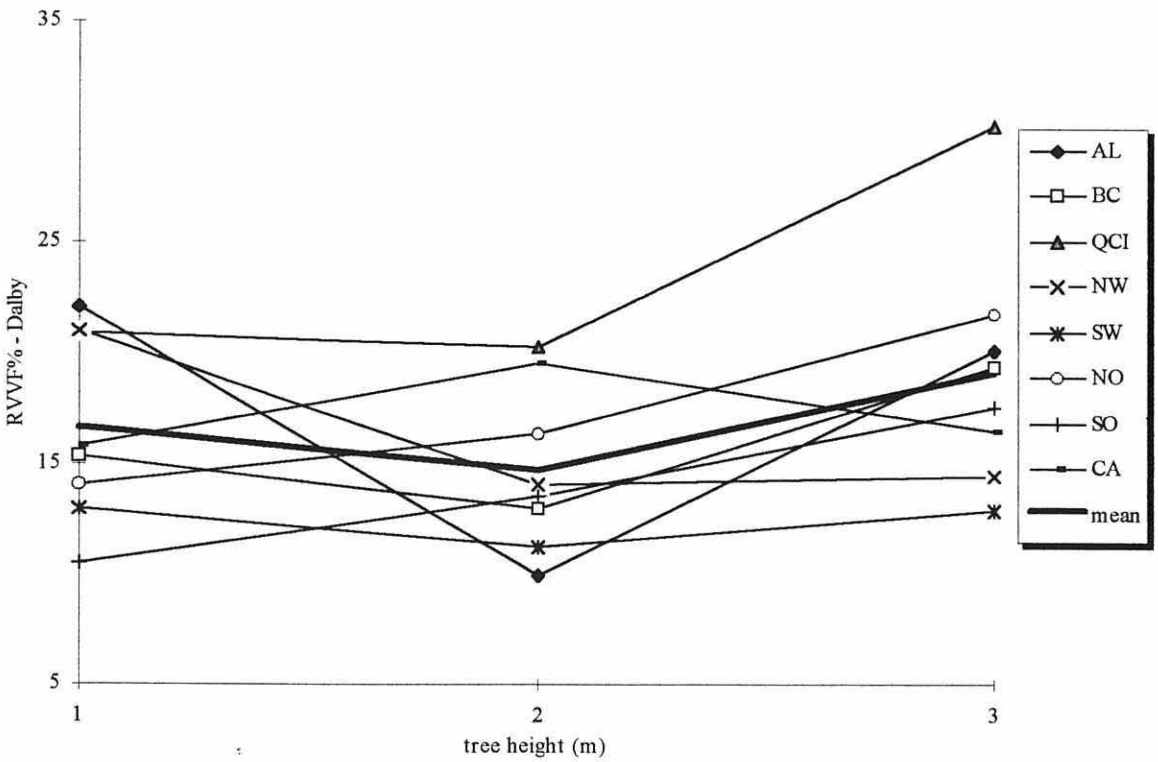


Figure 5.10. Vertical variation of RVVF% in (a) Rhondda and (b) Dalby within trees.

Examination of the overall means (Table 5.1) presented within Figures 5.9 and 5.10 on a bigger scale (Figure 5.11) reveals that the Dalby trees showed greater difference between LVVF% and RVVF%. These differences did not appear to be consistent with height within the tree. On the other hand in Rhondda, the mean values of LVVF% and RVVF% were closer to each other at each height (Table 5.1 and Figure 5.11).

Table 5.1. Comparison of changes of LVVF% and RVVF% within the height from base to apex of the tree in each site.

		tree height (m)			
site	permeability	1.3	2.3	3.3	mean
Overall mean	LVVF%	57.9	60.9	56.9	58.6
Overall mean	RVVF%	21.2	17.4	17.7	18.8
Rhondda (R)	LVVF%	50.7	57.4	51.9	53.3
Rhondda (R)	RVVF%	25.9	19.9	16.2	20.7
Dalby (D)	LVVF%	65.0	64.3	61.9	63.7
Dalby (D)	RVVF%	16.6	14.7	19.1	16.8

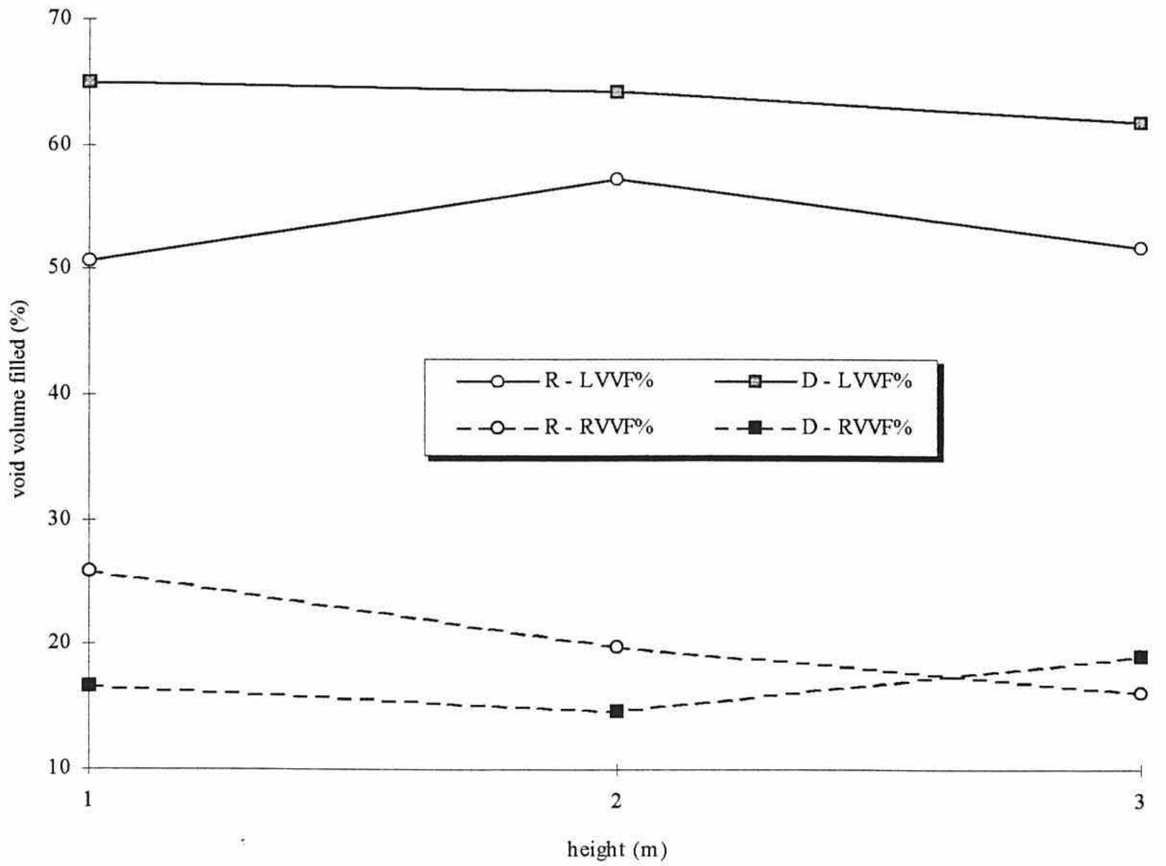


Figure 5.11. Comparison of changes of LVVF% and RVVF% in Rhondda and Dalby.

As was stated in Chapter 4, the correlations between LVVF% and RVVF% were poor at the height level. Although the radial permeability is only poorly correlated with longitudinal permeability (Dinwoodie, 1981), there is no doubt that while fluid is flowing longitudinally some may also flow from the axial tracheids into the ray tracheids via unaspirated bordered pits and then move radially along the ray tracheids (Retallick and Banks, 1987).

Likewise, when the fluid flows radially some goes into axial tracheids from either the ray tracheids (via unaspirated bordered pits) or the ray parenchyma cells through the cross-field pits and then moves longitudinally along the axial tracheids (McQuire, 1970).

If fluid flows from a ray into one axial tracheid as suggested above, the collapse of the membranes of the bordered pits (or unaspirated bordered pits in the latewood bands) on the radial walls would also permit transverse and vertical movement into other tracheids in the same tangential plane.

Although the LVVF% was greater at all the three heights in Dalby than that for Rhondda, the flow from the axial tracheid into the ray (i.e. ray tracheid) tended to be low in Dalby as indicated by the low RVVF%. As mentioned above, the lateral re-distribution would be quite possible in the latewood bands (but not in the earlywood) due to the majority of unaspirated bordered pits. It is therefore stated that this may have a strong influence on the differences in both longitudinal and radial permeability of these two sites.

Relation of Longitudinal Permeability and Density

Wood with low density usually retains more preservative (Koch, 1972) due to a function of high void volume (Kollmann and Cote, 1968) or as stated by Nicholas and Siau (1973) the fractional void volume (porosity) of wood determines the maximum amount of treating solution that can be injected into the wood structure. Therefore, it was expected that the trend of LVVF% would approximately follow an inverse trend with density in correspondence of the increasing trend of porosity from base to apex of the tree.

At Heights

However, the results at the centre and the top height did not support this expectation and according to McQuire (1970) obviously some other factors such as the percentage of pits aspirated, or resistance of the bordered pit membranes to rupturing under pressure must also be important effect for the relatively poor result of LVVF% at the 3.3 m height in the tree. This statement has been sustained with most seed origins. The lowest LVVF% occurred at the 3.3 m height, although it was the highest value of BC (Dalby). The trend of LVVF% also paralleled with that for density in CA of both sites, and AL and NO in Dalby.

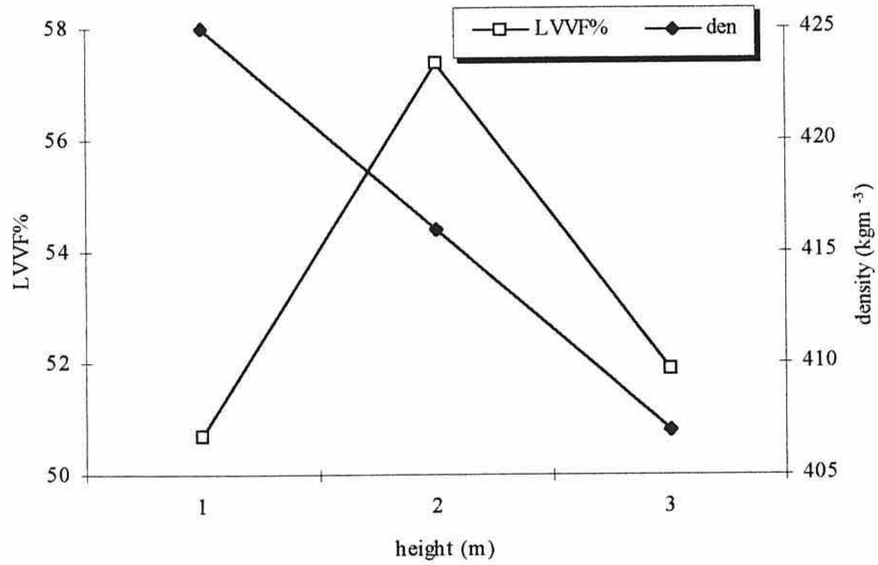
Longitudinal permeability is also related to tracheid length since treatable spruce (*Picea* spp.) and Douglas-fir (*Pseudotsuga menzeisii*) specimens are known to have longer tracheids (Liese and Bauch, 1967; Baines, 1986), and to have larger lumina (Fleischer, 1950). The general trend for tracheid length also shows a slight decrease towards the base of the stem (Dinwoodie, 1963).

Therefore, the highest value of LVVF% was obtained at the centre (2.3 m) of the trees where density was moderately low. This may explain the greater longitudinal uptake because of the many thick-walled cells which are likely to have a greater number of unaspirated bordered pits. According to Stamm (1964) and Siau (1984), there are smaller and fewer pits in latewood tracheids than in earlywood and generally fewer pits of smaller size on the tangential surfaces of all longitudinal tracheids. The thicker strands and tighter margo texture in latewood pits, their smaller diameter, and the configuration of the pit chamber contribute to their stiffness and resistance to aspiration (Liese and Bauch, 1966; Comstock and Cote, 1968; Petty, 1970), and thus latewood is more permeable than earlywood (Petty and Preston, 1969).

The lowest value of LVVF% which occurred at the top of the trees could also be associated with wider growth rings. There may be a tendency for some inclusion of juvenile wood at the top where the axial tracheids are shorter and are narrower.

Density within trees were significantly correlated with LVVF% up the stem especially in Dalby. As is shown in Figure 5.12, in Dalby, a decrease in LVVF% from 65.0 to 64.3 and fall to 61.9 was paralleled by a corresponding decrease in density (kgm^{-3}) from 418 to 409 and drop to 397. Although there was similar pattern in Rhondda at 2.3 m and 3.3 m heights, the highest density did not result highest LVVF% at 1.3 m height of the tree. However, the reason for the low LVVF% at the base in Rhondda may be related to the high RVVF%.

(a) Rhondda



(b) Dalby

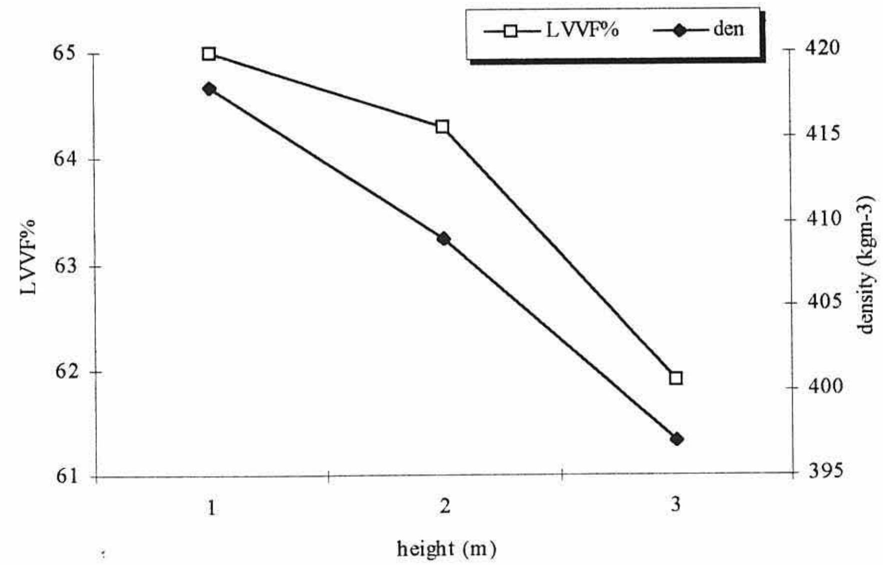


Figure 5.12. Comparison of changes of LVVF% and density within tree of (a) Rhondda, and (b) Dalby.

5.2.2 Between Tree Variation

As is explained in Section 5.2.1 high LVVF% was associated with higher tree volume (Dalby) due to a greater porosity which was accompanied by lower density (Tiemann, 1944; Richardson, 1978). Consequently, the faster grown Dalby trees had more LVVF% than in the slower grown Rhondda trees (Figure 5.13). However, the trees of Rhondda were more treated radially as compared to Dalby trees (Figure 5.14).

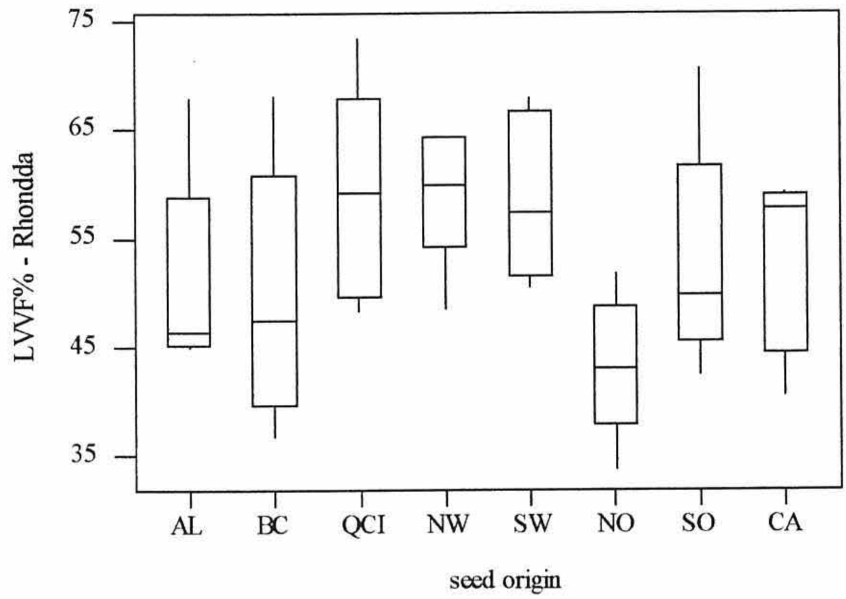
Since it was suggested that the trees of QCI, NW, SW and NO should be selected for more plantations as all grow well with a good density, considered seed origins were identified for producing the wood of adequate permeability. Individually, the trees of QCI and NW in both sites had higher than average LVVF% and RVVF%, whilst in either site the trees of NO and SO had a lower than average LVVF% and RVVF% respectively (Table 5.2).

Therefore, it may be suggested that the trees from the seed origins QCI and NW should be particularly planted to produce wood of adequate density and better permeability.

Table 5.2. Comparison of the seed origins arranged in declining values according to means of LVVF% and RVVF% in Rhondda and Dalby.

Longitudinal Permeability				Radial Permeability			
LVVF%	Rhondda	Dalby	LVVF%	RVVF%	Rhondda	Dalby	RVVF%
59.4	NW	SO	71.0	25.4	QCI	QCI	23.8
58.8	QCI	QCI	69.0	23.9	AL	AL	17.3
58.8	SW	NW	68.5	22.9	NW	NO	17.3
53.3	**mean**	**mean**	**63.7**	21.8	BC	CA	17.2
52.9	CA	BC	62.9	**20.6**	**mean**	**mean**	**16.7**
52.8	SO	SW	61.1	19.9	SW	NW	16.4
50.9	AL	CA	60.2	18.1	NO	BC	15.9
49.7	BC	NO	58.6	17.6	CA	SO	13.8
43.2	NO	AL	58.5	15.6	SO	SW	12.3

(a) Rhondda



(b) Dalby

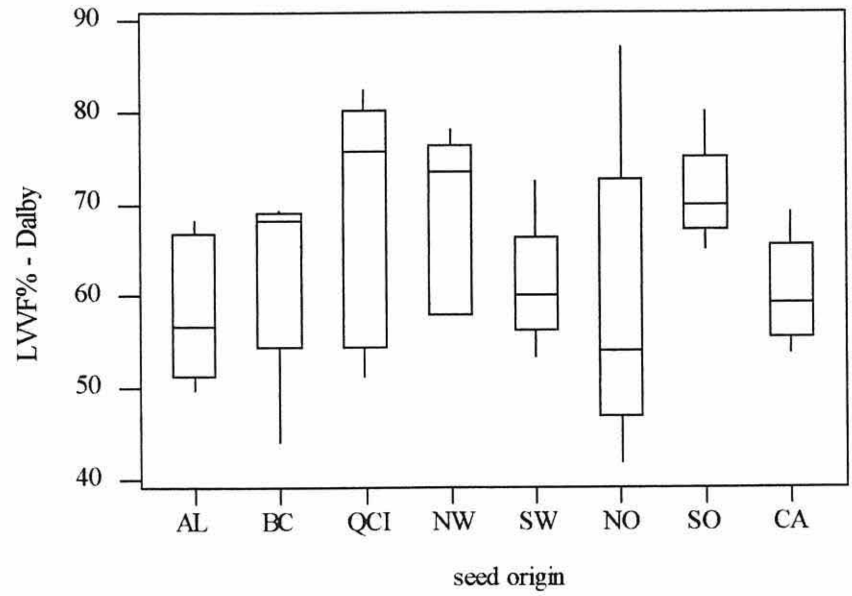
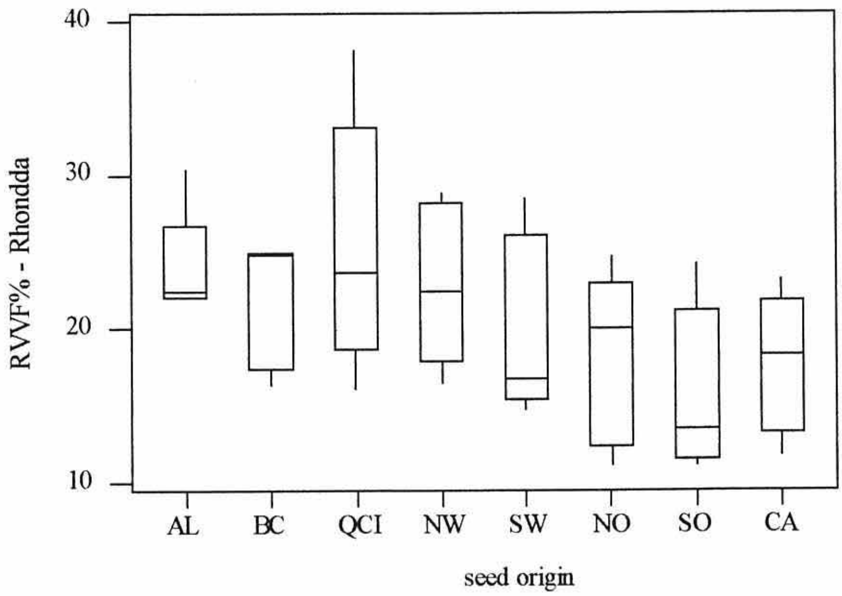


Figure 5.13. Distribution of LVVF% between trees of origins in (a) Rhondda, (b) Dalby.

(a) Rhondda



(b) Dalby

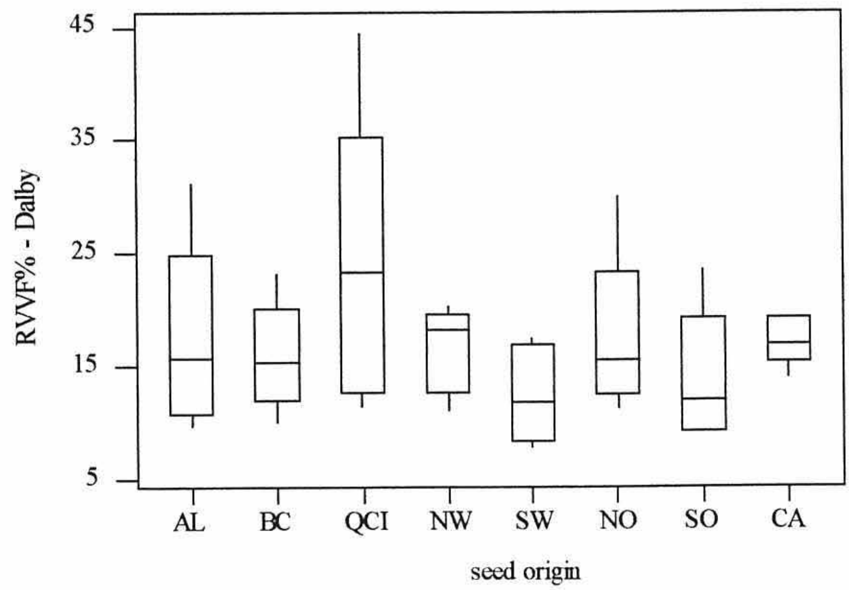


Figure 5.14. Distribution of RVVF% between trees of origins in (a) Rhondda, (b) Dalby.

5.2.3 Between Seed Origin Variation

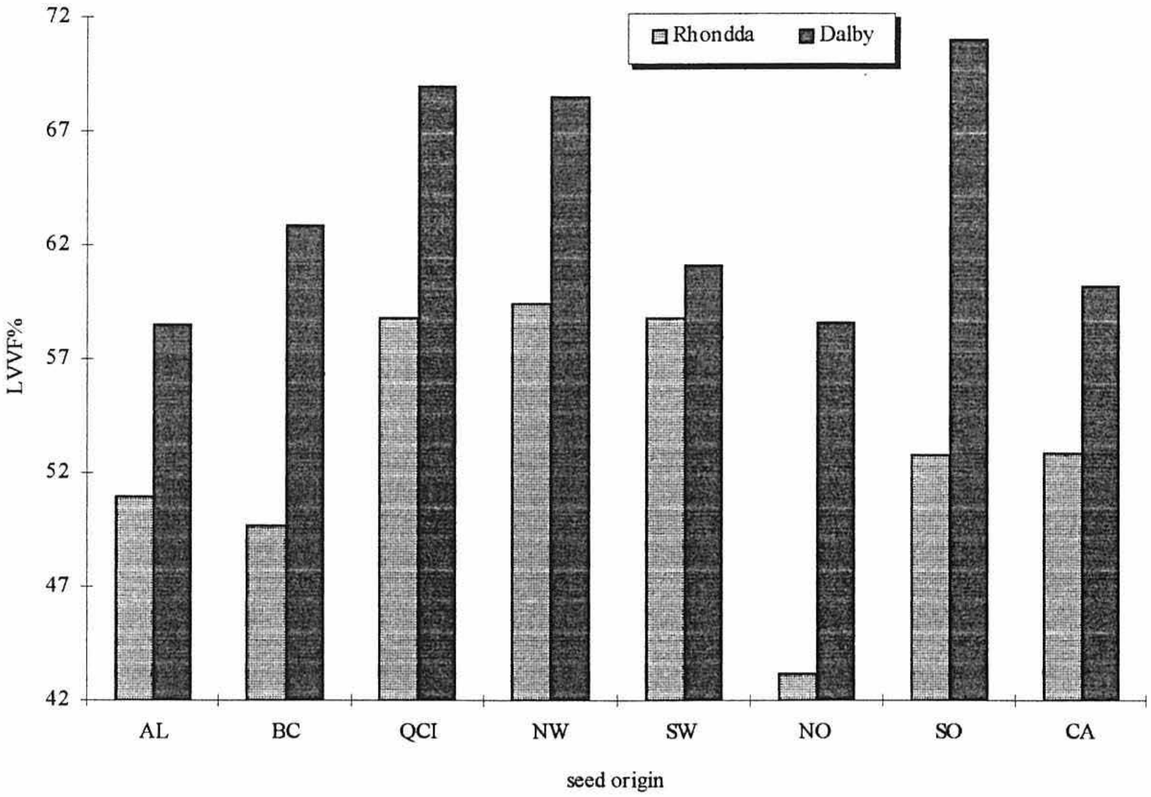
In the discussion of the permeability trial dealing with the correlation between density and void volume filled (section 5.2.1) significant correlations were only found between density and LVVF% and there were no significant correlations with RVVF%. Since the bulk of the tissue is composed of longitudinal tracheids and latewood percentage is related to density and latewood forms the residual pathway of flow the correlation of LVVF% and density is not surprising. Furthermore the lack of correlation between density and RVVF% is not surprising either. However, as shown in Table 4.2, there are significant differences in LVVF% and RVVF% between seed origins.

There are definite differences between RVVF% and LVVF% values which are significant at the seed origins level and are presented in Figure 5.15. In all cases the seed origins grown at Rhondda show lower LVVF% permeability than those at Dalby but the overall pattern of the seed origin is similar. The overall pattern is again similar for RVVF% permeability (Figure 5.15) but the RVVF% is greater in Rhondda than Dalby.

The results obtained in this study generally show that LVVF% in the seed origins QCI (63.9) and NW (63.9) which are located in the central part of the natural distribution of Sitka spruce were greater in comparison to NO (50.9) which is located in the south. Moreover, the greatest radial permeability (RVVF%) also occurred in both QCI (24.6) and NW (19.7) in comparison to SO which is located in the south (14.8).

As shown in Figure 5.15, RVVF% values for the southern origins NO, SO and CA are similar at the two sites, although SO showed low RVVF% and high LVVF%. On the other hand, QCI had high radial and longitudinal permeability in both sites. This situation has been shown in some *Pinus* spp. by McQuire (1970) and was explained by the interconnections between the different flow pathways in the different connections. Although Sitka spruce has different anatomical features (extent of aspiration, crossfield pit structure, latewood proportion), it is possible that this is the case for QCI. Further work on the anatomical features of QCI are in the following chapter.

(a) LVVF%



(b) RVVF%

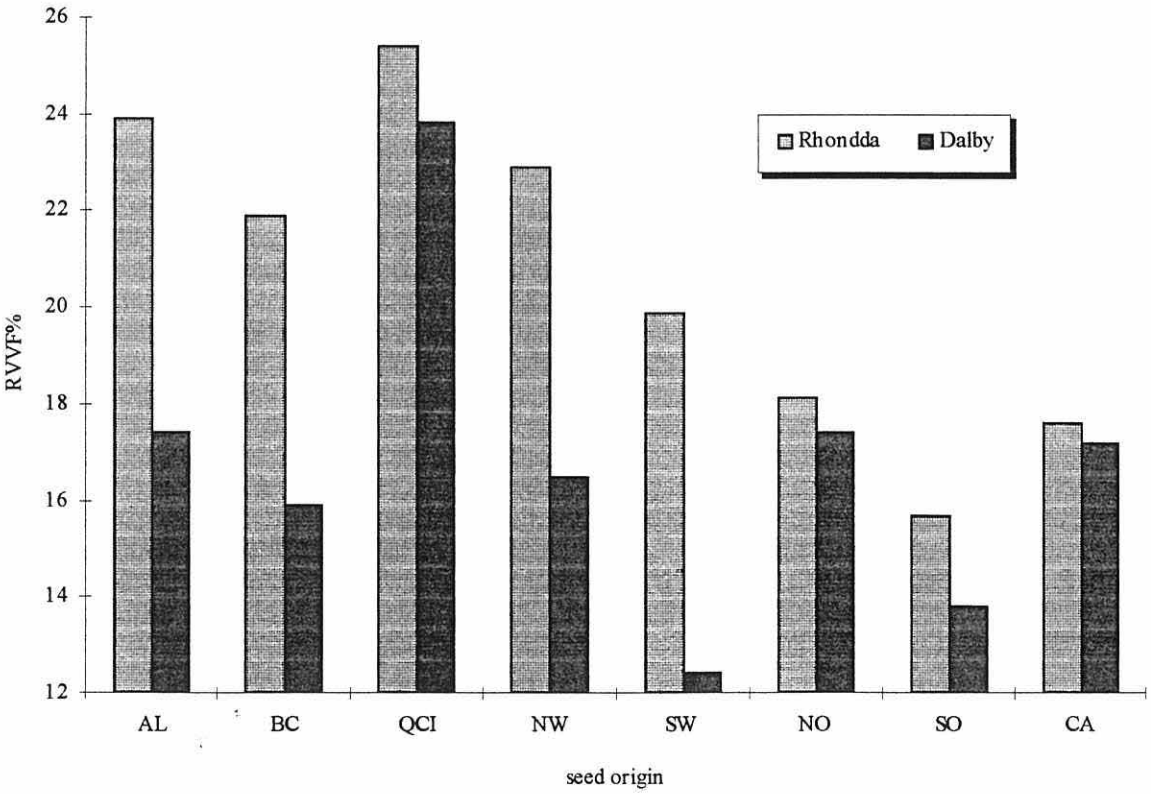


Figure 5.15. The variation of (a) LVVF%, (b) RVVF% between seed origins in both sites.

The above comments highlight QCI as an interesting seed origin: in Rhondda it was ranked third LVVF% and second in Dalby (Figure 5.15). Also, SO, highlighted above as low RVVF% was least treated in Rhondda and second lowest in Dalby (Figure 5.15).

It appears that there are reasonable explanations for differences in longitudinal permeability and that the differences are linked to density which is in current breeding programs. Furthermore, the major aspects of longitudinal permeability are associated to post-harvest processing, e.g. drying. Moreover, it is not surprising that the radial permeability is not correlated with any of the gross features seen or with longitudinal permeability as the features seen relate more to axial tracheids, i.e. the longitudinal pathway, which account for some 95% of the wood volume (Fengel and Wegener, 1989).

Little is known however about radial permeability (see section 2.6.2) but differences seen in this study between the seed origins QCI and SO deserve greater investigation. Thus, microscopic analysis of the ray features was carried out to examine the ray structure of these two seed origins.

6 RADIAL PERMEABILITY OF SITKA SPRUCE AS AFFECTED BY WOOD STRUCTURE

6.1 Introduction

As presented in Chapter 4, the results obtained in this study generally show that the greatest longitudinal and radial permeability (i.e. by overall means of LVVF% and RVVF%) both occurred in QCI in contrast to SO that was ranked third LVVF% and the least RVVF%. The results of the permeability experiment highlight both QCI and SO as interesting seed origins. When analysed by site for LVVF%, QCI was third in Rhondda and second in Dalby while it was first for RVVF% on both sites. On the other hand, SO was the least treated radially in Rhondda and was second lowest in Dalby.

As discussed in Chapter 5, it appears that there are reasonable explanations for differences in longitudinal permeability and that the differences are linked to density which is in current breeding programs. Furthermore, the major aspects of longitudinal permeability are associated to post-harvest processing, e.g. drying. Little is known however about radial permeability but differences seen in this study between QCI and SO deserve greater investigation. Therefore, in this chapter the anatomical structure of both uniseriate and fusiform ray tissues have been examined by light and scanning electron microscopy (and microscopic images were analysed by image analyser) to explain the differences in radial uptake between the extremes in the radial treatment data, i.e. between QCI (Rhondda) and SO (Dalby). A broader sample of origins and sites would have been chosen but there was insufficient time for this.

6.2 Material and Methods of Anatomical Analysis

Emphasis on anatomical analysis was given to the seed origin extremes of RVVF% QCI (25.4 %) and SO (13.8 %) from the trial sites Rhondda and Dalby. As is shown in Table 6.1, the greatest percentage of void volume filled by preservative radially occurred at the 2 m height in tree 1 seed origin QCI of Rhondda with some 48.20 % compared with the lowest in tree 4 SO of Dalby (7.04 %), thus these extreme trees of the two seed origins have been chosen. Although these represent means of only 3 samples at this height, important differences should be apparent. Data obtained only however refer to these two trees at this height examined and further work is desirable to confirm observations that follow in this chapter.

Table 6.1. Means of density (kgm^{-3}), and the void volume filled (%) in both radial and longitudinal flow directions in 2 m height of all the trees of QCI and SO in both trial sites.

	Rhondda			Dalby		
tree	density	RVVF%	LVVF%	density	RVVF%	LVVF%
QCI - t1	422.06	48.20 **max**	62.96	469.02	20.93	81.35
QCI - t2	499.42	22.03	59.52	373.48	16.14	62.95
QCI - t3	404.31	33.81	53.37	418.89	27.49 max	81.22
QCI - t4	386.98	21.92	46.66	368.88	9.47	54.09
QCI - t5	414.65	28.78	78.78	343.09	27.43	71.76
SO - t1	527.24	12.56	51.38	456.78	8.99	83.48
SO - t2	472.90	12.26	51.53	436.81	16.24	74.67
SO - t3	466.46	16.19	48.13	322.59	23.07	63.45
SO - t4	421.39	10.02 min	47.14	404.10	7.04 **min**	65.19
SO - t5	434.90	20.86	78.69	400.67	11.90	73.84

t = tree

Thereafter, the following techniques were used to examine the structures which might have some bearing on the radial flow of liquids into the wood specimens of QCI (Rhondda) and SO (Dalby) used in previous density and both radial and longitudinal permeability studies.

6.2.1 Light Microscopy: Seescan Image Analyser (SIA)

Measurement of height and width of both ray parenchyma and ray tracheid cells in either the uniseriate or the fusiform ray tissues and their cell wall thickness, height and width of both resin canals and epithelial cells (with also the intercellular spaces) in fusiform ray tissue were carried out using a monochrome (64 grey level) Image Analysis System (Seescan plc) which will be referred as SIA (Seescan Image Analyser) in this chapter.

The video camera (Phillips, XC-77CE) of the SIA (TPL 3V47) was connected to the light microscope (Leitz, laborlux 12) and a RLS section mounted on a slide was analysed. The area analysed was located and the image was then captured and transferred to its VDU screen for use interactively with the image analysis package. This system allowed the user to directly measure the distances on the screen between any two points located across individual cells via the use of a mouse. The line drawn between the chosen points was automatically measured, and the information was then processed and displayed as a number of pixels values of which were then recorded and converted to metric units (Clauson and Wilson, 1991). Calibration of the measurements was done by placing a graticule of 1/100 mm on the microscope. The measurement on the graticule was captured on the image analysis and the length of the graticule was measured in pixel size. This method was used as the basis for converting pixel to mm for each objective lens as shown in Table 6.2 below.

Table 6.2 Conversion table from pixel units to micrometers (Sulaiman, 1993).

objective lens	pixel units	μm
10	48	100
40	195	100
100	475	100

As is represented in Figure 6.1, the internal structure of the uniseriate and the fusiform ray tissues was investigated from tangential-longitudinal sections (TLS) and radial-longitudinal sections (RLS) with tangential and radial sections which were cut from the sapwood zone of the centre discs (2 m height above ground level) of the selected trees of QCI and SO. Examination of the condition of cross-field pits was made from the RLS along a transect line extending from bark to a depth of 30 mm, whereas the dimensional measurements of both ray tracheids and ray parenchyma cells, and also the resin canals were made from TLS.

The experimental strips of size about 30 mm x 5 mm x 5 mm were saturated with deionised water for TLS and RLS and 15 μm sections were cut with a sledge microtome. The sections which were at first curled were flattened by being placed on a microscope slide using a small brush and then sandwiched between another slide after mounting in 20 % glycerol. These were then clamped together with clothes pegs and placed on a warm plate. The sections were then viewed with a x40 objective lens.

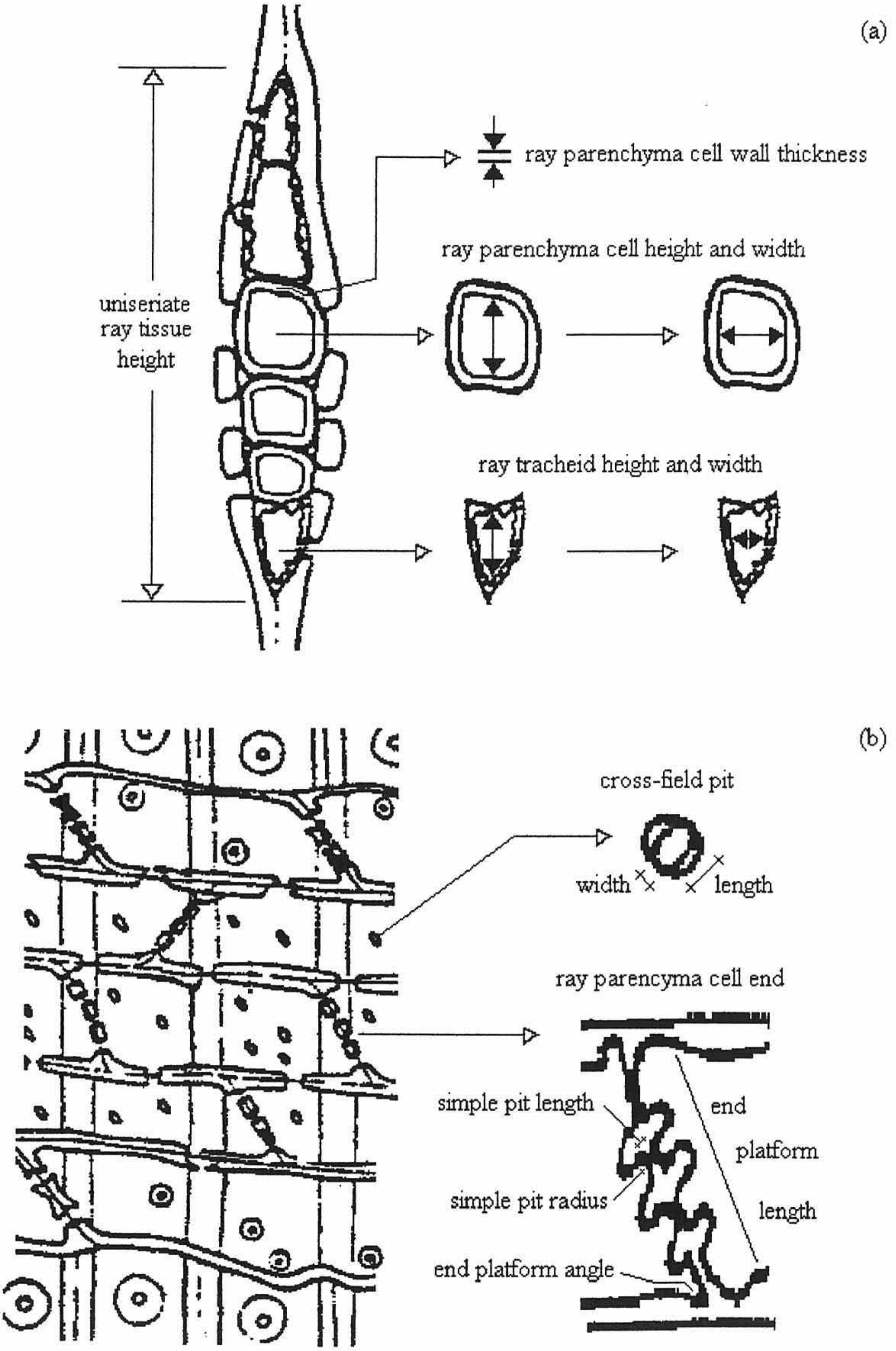


Figure 6.1. Schematic representation of (a) TLS and (b) RLS for determinations of the internal structures of the uniseriate ray tissue (after Iivessalo-Pfäffli, 1967).

6.2.2 Scanning Electron Microscopy (SEM)

The use of the light microscope has to some extent been superseded in the study of wood anatomy of Sitka spruce by the SEM (Scanning Electron Microscope) which was particularly used for examining the cross-field pits in QCI and SO since the condition of pit membranes and size of the apertures was determined easily by examining the radial-longitudinal surfaces.

As mentioned by Barnett (1988), it was found that microtome knives of the type used in light microscopy were unsatisfactory to prepare the ideal wood samples for the SEM as they left score marks across the prepared surface, and the cut rims of cells were ragged (Ladislav, 1985). Hence, the best way to obtain the clean surfaces was to use a hand-held razor blade in the manner described by Exley *et al.* (1974) using the wood material which was kept wet by immersion in one of the conventional light microscope fixatives such as formalin: acetic acid: alcohol, FAA (O`Brien and McCully, 1981).

Therefore, to examine the cross-field pits, small blocks (with a cutting face of no more than 5 mm square in all the three sections) were split along an approximate radial plane. The split, thus obtained, showed the best orientation of the rays along their length and they were then further cut using the edge of a fresh single edged razor blade (Stainless, TAAB), following guidelines described by Barnett (1988). After adhesion onto aluminium stubs with double-sided tape and coating with gold to a nominal thickness of 400Å in a Polaron E5000 sputter coater, the wood was examined at 10KV in an Hitachi S520 SEM.

Digital images (taken at a magnification of 1000x) were captured at various points across growth rings attempting to follow individual rays and printed on a Sony thermal image printer. Images were overlapped so that a photo montage could be constructed to show the variation in cross-field pits across a growth ring. Where a ray did not span across an entire growth ring due to oblique sectioning a number of areas were imaged which overlapped axially and collectively represented an entire growth ring. The pictures were then analysed by SIA to determine the size of cross-field pits and their variation across entire growth rings.

6.3 Results

6.3.1 Uniseriate Ray Tissue

The mean height (h), width (w) and quantitative area (qa) of the uniseriate ray tissue (UR), and adding to the first two initials mean lumen area (d) of both ray parenchyma cell (P) and ray tracheid (T) of both QCI (Rhondda) and SO (Dalby) are given in Table 6.3 with indication of significance for differences between the two trial seed origins.

Table 6.3. Means of parameters measured by light microscopy in uniseriate ray tissue in QCI and SO (n = 10).

parameter measured in uniseriate ray tissue	QCI	SO	p	s
Pn - number of ray parenchyma cells	10	8	0.172	NS
Tn - number of ray tracheids	2	2		
URh - total uniseriate ray tissue height (μm)	176.0	135.3	0.098	NS
Ph - total ray parenchyma cell height (μm)	139.7	104.0	0.182	NS
Th - total ray tracheid height (μm)	23.7	17.0	0.029	*
Pt - total ray parenchyma cell wall thickness (μm)	5.1	5.7	0.481	NS
Tt - total ray tracheid cell wall thickness (μm)	7.5	8.6	0.133	NS
URqa - quantitative area of uniseriate ray tissue (μm^2)	1.59	1.17	0.061	NS
Pd - mean ray parenchyma lumen area (μm^2)	0.071	0.068	0.422	NS
Td - mean ray tracheid lumen area (μm^2)	0.038	0.022	0.038	*
URw - uniseriate ray tissue width (μm)	11.67	11.27	0.578	NS
Pw - mean ray parenchyma cell width (μm)	6.41	6.26	0.414	NS
Tw - mean ray tracheid width (μm)	4.22	2.84	0.024	*

p = p - value, s = the indication of significance, NS = not significant, * = 95%

Generally, the results showed that QCI had the greatest amount of the uniseriate ray tissue when both the total value of the ray parenchyma cells or the ray tracheids are examined. The total uniseriate ray tissue height (URh), including the heights of the total ray parenchyma cells and ray tracheids and with their cell wall thickness, was greater in QCI (176.0 μm) than in SO (135.3 μm) although the differences were not statistically significant (p = 0.098).

Both the total height of the ray parenchyma cells (Ph) and the ray tracheids (Th) were greater in QCI (139.7 μm, 23.7 μm) than in SO (104.0 μm, 17.0 μm). The difference was not significant in Ph (p = 0.182) but was for in Th (p = 0.029).

Likewise, the mean width of both ray parenchyma cells (Pw) and the ray tracheids (Tw) were greater in QCI (6.41 μm, 4.22 μm) compared to SO (6.26 μm, 2.84 μm). Again, the differences in Pw were not significant ($p = 0.414$) while in Tw they were significant ($p = 0.024$).

Therefore, as is also seen in Figure 6.2., the quantitative area of the uniseriate ray tissue (URqa) in radial-longitudinal section was larger in QCI (1.59 μm^2) than in SO (1.17 μm^2). This is reflected in the average number of the ray cells in the uniseriate ray tissue where it was greater in QCI (10) than in SO (8). This was not however statistically significant ($p = 0.172$).

When all these variations are considered to put together, the total height of the ray parenchyma cell was seen to be the most important factor for differences of the total amount of the uniseriate ray tissue between QCI and SO

(a) QCI - Rhondda (b) SO - Dalby

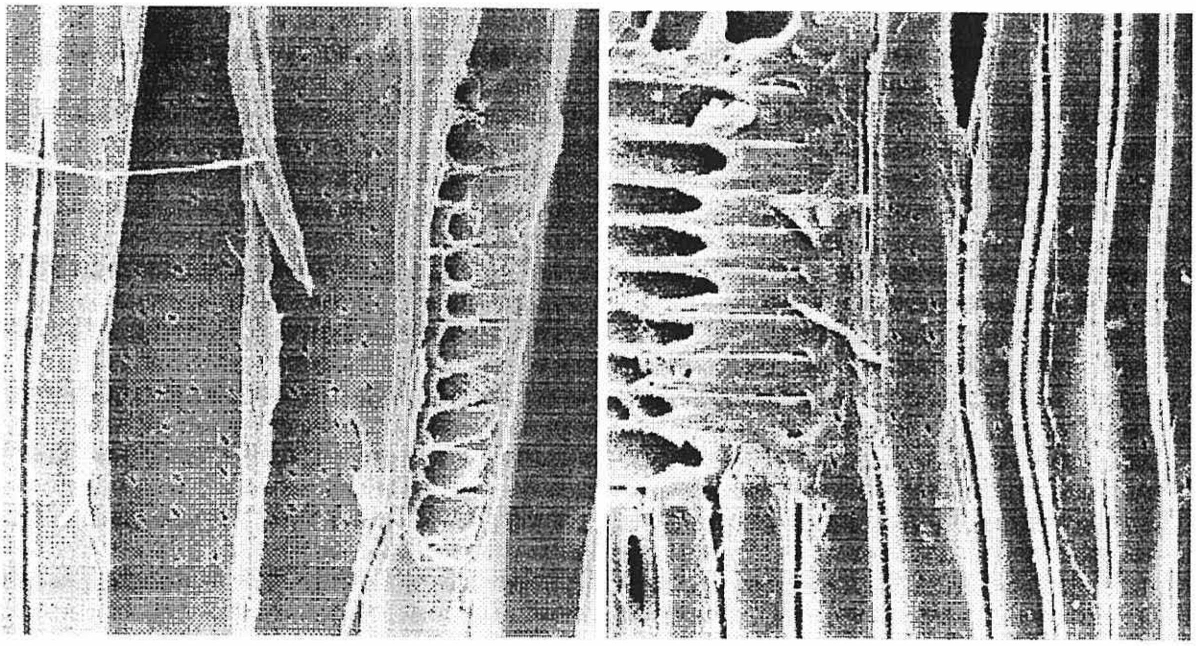


Figure 6.2. General view of the uniseriate ray tissue in RLS showing the quantitative differences in (a) QCI (Rhondda) and (b) SO (Dalby) (x 500).

6.3.2 Cross-field Pits

The number of cells in a given area, cross-field pits (CFP) in ray parenchyma cells and their mean diameters in earlywood (E) and latewood (L) were estimated for the seed origins QCI and SO by image analysis of SEM pictures (Table 6.4).

Table 6.4. Number of axial tracheids intersectioned with ray parenchyma cells, the total number of cross-field pits and their mean diameters either in L or E both in QCI and SO.

	QCI		SO	
parameter	latewood	earlywood	latewood	earlywood
number of axial tracheids	27	61	26	22
total number of CFP	123	550	98	250
mean no of CFP per tracheid*	5	9	4	11
total CFP area (μm^2)	199	928	22	996
mean CFP area (μm^2)	1.62	1.82	0.22	3.98

* within the cross-field area examined

The total number of cross-field pits (CFP) in both latewood (L) and earlywood (E) areas was greater in QCI (123, 550) than in SO (98, 250) because the total amount of the uniseriate ray tissue was greatest in QCI.

The mean CFP diameter in the latewood of QCI (1.62) was seven times larger than SO (0.22) although that in the earlywood of SO (3.98) was two times greater than QCI (1.82). As is also seen in Table 6.5. and Figures 6.3 and 6.4, the range of CFP diameters was very small in QCI (0.20) and the difference between the latewood and the earlywood cells was not statistically significant ($p = 0.075$) whereas in SO the range was notably huge (3.76) and highly significant ($p = 0.001$).

Table 6.5. The differences CFP diameter of mean L and E cross-field pits in QCI and SO.

seed origin	latewood (μm^2)	earlywood (μm^2)	p	s
QCI	1.62	1.82	0.075	NS
SO	0.22	3.98	0.000	***

p = p - value, s = the indication of significance, NS = not significant, *** = 99.9%
L = latewood, E = earlywood

(a) latewood (b) earlywood

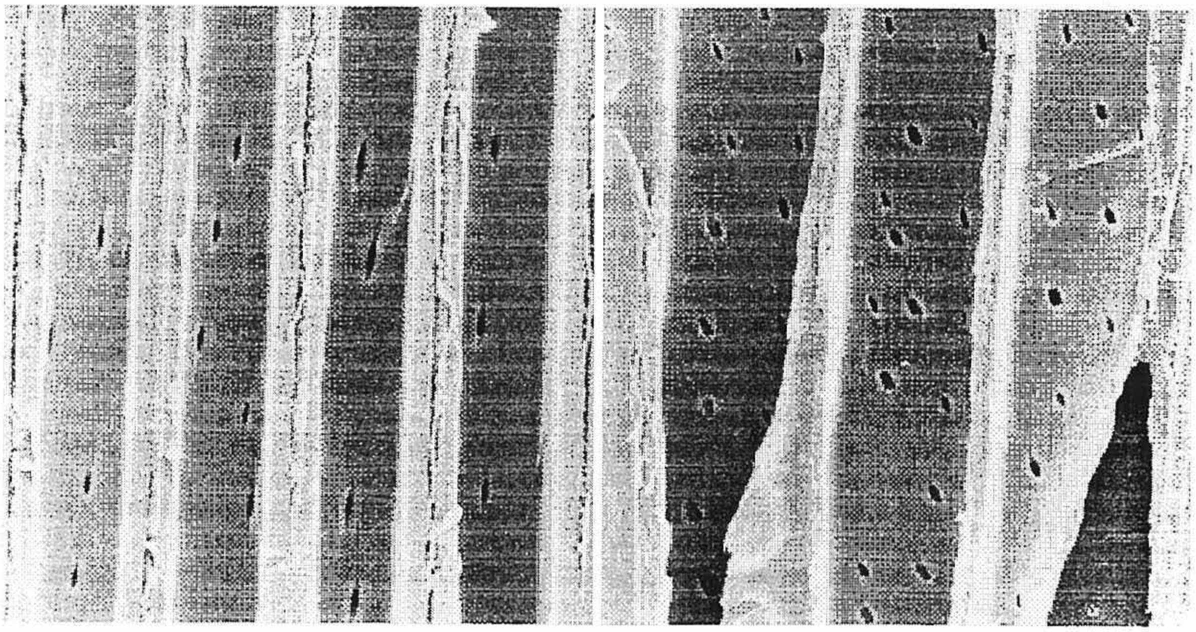


Figure 6.3. Comparison of changes in mean cross-field pit diameter per cross-field in each axial tracheid in (a) latewood and (b) earlywood of QCI (Rhondda) (x 1000)

(c) latewood (d) earlywood

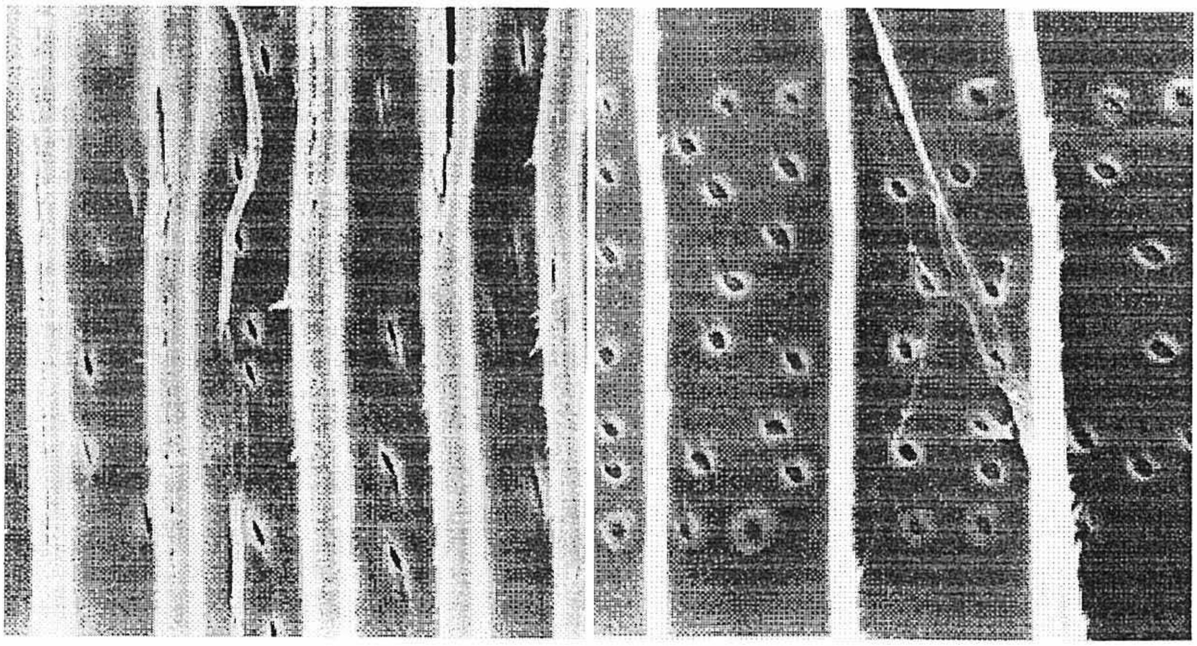


Figure 6.4. Comparison of changes in mean cross-field pit diameter per cross-field in each axial tracheid in (c) latewood and (d) earlywood of SO (Dalby) (x 1000).

The mean cross-field pit diameter across transects of latewood and earlywood show considerable variation in QCI with a slight systematic increase in the middle of the growth rings (Figure 6.5, cell nos: 40 - 50). Conversely, the latewood variation in SO is low compared to the earlywood variation and there is an abrupt transition zone at the growth ring boundary (Figure 6.5, cell nos: 25 - 30).

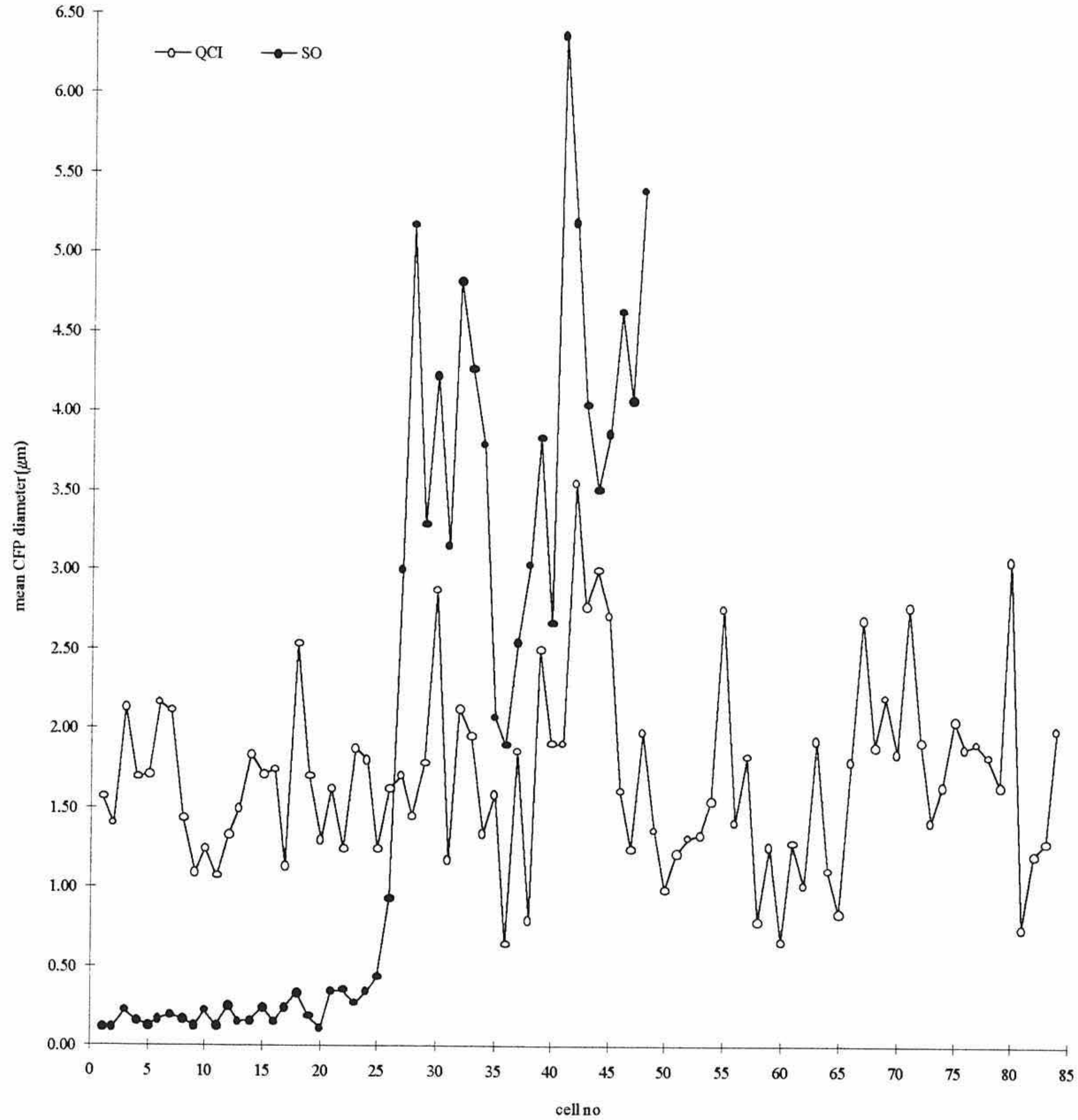


Figure 6.5. The schematic illustration of the mean cross-field pit diameter per cross-field in each axial tracheid along the examined rays by scanning electron microscopy. The ranges of the cross-field pits for latewood is represented by 1 - 27 in QCI and 1 - 26 in SO.

In both seed origins, the mean diameter of cross-field pits (CFP) in latewood and earlywood seemed to be inversely affected by the dimensions of the ray parenchyma cell in the uniseriate ray tissue (Table 6.6). Linear regression showed that the total ray tracheid cell height (Th) accounted for some variation in the mean diameter of CFP in both latewood and earlywood ($R^2 = 0.238$, $p = 0.029$) and the total height of the uniseriate ray tissue (URh). This comprises the total height of both the ray parenchyma cells and the ray tracheids also had an important effect ($R^2 = 0.145$, $p = 0.098$). Similarly, the total ray parenchyma cell height (Ph) accounted for a small amount ($R^2 = 0.097$, $p = 0.182$) of the variation in the mean diameter of CFP in either case, although it was not statistically significant.

Table 6.6. Linear regression equations between the mean diameter of cross-field pits and the dimensions of ray parenchyma cell in (a) latewood and (b) earlywood of both QCI and SO.

EQUATION	R^2	p	s
(a) latewood			
CFPd = 0.187 + 4.74 URh	0.145	0.098	NS
CFPd = 0.457 + 3.8 Ph	0.097	0.182	NS
CFPd = - 0.099 + 50 Th	0.238	0.029	*
CFPd = 0.068 + 618 URqa	0.182	0.061	NS
(b) earlywood			
CFPd = 4.03 - 7.32 URh	0.145	0.098	NS
CFPd = 3.61 - 5.87 Ph	0.097	0.182	NS
CFPd = 4.47 - 77.2 Th	0.238	0.029	*
CFPd = 4.22 - 953 URqa	0.182	0.061	NS

CFPd = mean diameter of cross-field pit

In latewood, the regression between the total height of the ray uniseriate ray tissue (URh), ray parenchyma cell (PH), ray tracheid (Th) and the mean CFP diameter was positive whereas in earlywood it was negative. This means that wider ray parenchyma cell widths and taller ray parenchyma cell heights result in a larger diameter of cross-field pits in latewood with smaller diameter of CFP in earlywood, and narrower ray parenchyma cell widths and shorter ray parenchyma cell heights may produce the larger diameter of cross-field pits in earlywood with smaller diameter of CFP in latewood.

6.3.3 Ray Parenchyma Cell Ends: End Platforms

The ends of the ray parenchyma cells, detailed view of which given in Figure 6.6, were examined by light microscopy for each seed origin and mean results are given in Table 6.6.

(a) (b)

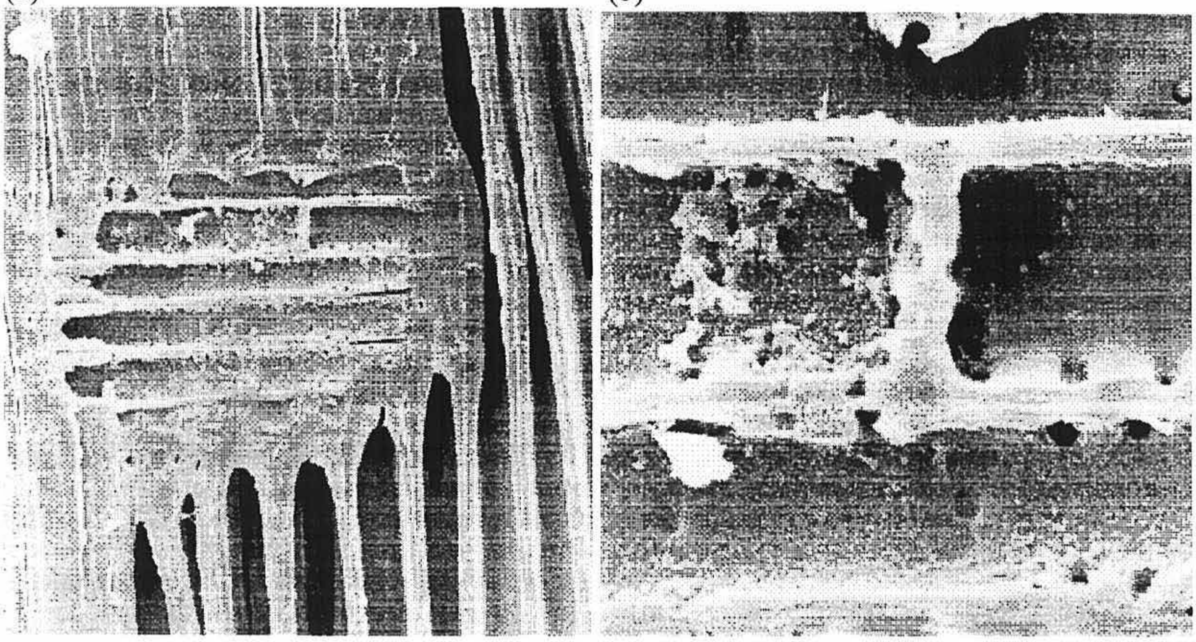


Figure 6.6. The general and detailed views of the uniseriate ray parenchyma cell ends (end platform). This pictures taken from the RLS of QCI (Rhondda) (a, x 250; b, x 1250)

As is seen in Table 6.7, The length of the end platform (i.e. the cell end where the simple pits are located) was longer in SO (21.2 μm) than in QCI (17.7 μm) and the height of the ray parenchyma cell void was shorter in SO (13 μm) than in QCI (14 μm) although the differences were not statistically significant. Besides, the end platform thickness (the length of the simple pit) was very highly significantly greater in SO (0.789 μm) than in QCI (0.573 μm), although measurement accuracy may be suspect at this level.

There were no differences in the average number of the simple pits on the end platform, although the mean diameter (radius) of simple pits was significantly larger in QCI (0.401 μm) than in SO (0.268 μm). The angle of the end platform in the ray parenchyma cells was almost similar (QCI: 82.8°, SO: 82.1°).

Table 6.7. Descriptive statistics of the actual situation of the end platform of the ray parenchyma cells in the seed origins QCI (Rhondda) and SO (Dalby).

parameter	QCI	SO	p	s
mean Ph (μm)	14	13	0.495	NS
end length (μm)	17.7	21.2	0.101	NS
end thickness (μm)	0.573	0.789	0.001	***
number of simple pit	4	5	0.517	NS
simple pit dia (μm)	0.401	0.268	0.031	*
platform angle (°)	82.8	82.1	0.284	NS

Table 6.8. Linear regression equations between the diameter of simple pits and the anatomy of the end platform of the ray parenchyma cells of QCI and SO.

EQUATION	R^2	p	s
SP dia = 0.000068 + 0.000058 SPn	0.006	0.041	*
SP dia = 0.000292 + 0.00219 end length	0.005	0.043	*
SP dia = 0.000275 + 0.0221 RPCvh	0.095	0.010	**
SP dia = 0.000508 - 0.254 end thickness	0.076	0.021	*
SP dia = - 0.00040 + 0.000009 platform angle	0.001	0.489	NS

SPn = number of simple pit, RPCvh = the height of the ray parenchyma cell void

6.3.4 Fusiform Ray Tissue

Data relating to the light microscope analysis of the fusiform ray tissue are given in Table 6.9. The quantitative area of the fusiform rays per ray (FRqa) was significantly (p = 0.000) greater in QCI (10.2 μm^2) than in SO (5.4 μm^2). Further, fusiform ray tissue was found to be taller and wider in QCI (244.3 μm, 37.8 μm) than in SO (180.1 μm, 27.0 μm). The difference in height was not statistically significant (p = 0.059) while the width was very highly significantly different (p = 0.000).

The dimension of the resin canal was also found 2x larger in QCI than in SO either vertically or horizontally. Both height and width of the resin canal (RCh, RCw) were significantly (p = 0.022, p = 0.010) greater in QCI (30.9 μm, 15.9 μm) than in SO (18.2 μm, 9.1 μm) with also the largest lumen area (QCI: 0.44 μm^2, SO: 0.13 μm^2).

The size characteristics of the ray parenchyma cells in fusiform ray tissue showed an almost inverse relationship to those of the initial findings of the uniseriate ray tissue. The fusiform ray parenchyma cell diameter (Pd) was significantly (p = 0.019) larger in QCI (0.059 μm^2)

than in SO (0.053 μm²). Each seed origin showed quite different results in the case of both total height and mean width for the fusiform ray parenchyma cell. QCI was slightly (p = 0.059) taller and was considerably (p = 0.019) wider in comparison to those of SO (QCI: 244.3 μm, 7.1 μm, SO: 180.1 μm, 6.5 μm). The number of cells per fusiform ray tissue (Pn) was also greater in QCI (23) than in SO (18), although the differences were not statistically significant (p = 0.096).

Likewise, the size components of the fusiform ray tracheid was conversely different in either seed origin although the differences in all the three cases (i.e. height, width, area) were not significant. The total fusiform ray tracheid height was greater (p = 0.175) in QCI (20.8 μm) than in SO (17.5 μm), the mean fusiform ray tracheid width was marginally (p = 0.667) wider in SO (3.9 μm) than in QCI (3.5 μm) but in spite of the variations between the height and width, the fusiform ray tracheid diameter was almost similar (p = 0.716) in both seed origins (QCI: 0.031 μm², SO: 0.028 μm²).

Table 6.9. Dimensions of the structural components of the fusiform ray tissue in the trial seed origins QCI (Rhondda) and SO (Dalby).

parameter measured in fusiform ray tissue	QCI	SO	p	s
number of ray parenchyma cell	23	18	0.096	NS
number of epithelial cell	5	6	0.203	NS
number of ray tracheid	4	3	0.198	NS
total fusiform ray tissue height (μm)	344.6	256.7	0.045	*
total ray parenchyma cell height (μm)	244.3	180.1	0.059	NS
total resin canal height (μm)	30.9	18.2	0.022	*
total ray tracheid height (μm)	20.8	17.5	0.175	NS
total epithelial cell height (μm)	9.7	6.7	0.104	NS
total ray parenchyma cell wall thickness (μm)	12.6	10.9	0.109	NS
total ray tracheid cell wall thickness (μm)	22.6	14.9	0.000	***
total epithelial cell wall thickness (μm)	3.6	8.4	0.000	***
quantitative area of fusiform ray tissue (μm²)	10.2	5.4	0.000	***
mean ray parenchyma cell diameter (μm²)	0.059	0.053	0.019	**
mean resin canal area (μm²)	0.44	0.13	0.023	*
mean ray tracheid lumen area (μm²)	0.031	0.028	0.716	NS
mean epithelial cell area (μm²)	0.034	0.018	0.000	***
fusiform ray tissue width (μm)	37.8	27.0	0.000	***
mean ray parenchyma cell width (μm)	7.1	6.5	0.021	*
mean resin canal width (μm)	15.9	9.1	0.010	**
mean ray tracheid width (μm)	3.5	3.9	0.667	NS
mean epithelial cell width (μm)	4.4	3.3	0.000	***

p = p-value, s = significance, NS = not significant, * = 95%, ** = 99%, *** = 99.9%

6.4 Discussion

In this chapter a number of the microscopic features of wood anatomy which could be expected to affect the rate and the amount of preservative transported in a radial direction (Erickson, 1964; Liese and Bauch, 1967; Banks, 1970; Petty, 1970; Siau, 1984; Baines, 1986; DeGroot and Kuster, 1986; Keith and Chauret, 1988) have been compared between the most (QCI, Rhondda) and the least (SO, Dalby) radially permeable samples. The features were examined and quantified in uniseriate and fusiform rays, and then analysed for significant differences.

6.4.1 Uniseriate Ray Tissue

For uniseriate rays, the following gross features were examined by light microscopy in TLS: height, width and quantitative area of the ray tissue, number of the ray parenchyma cells, their height, width and diameters and ray tracheid height, width and diameters. Of these features, the only features which were significantly different were the total height of the ray tracheids and their mean widths with their lumen area.

Ray Parenchyma Cells

The only feature which was significantly greater in the more radially permeable QCI was the total height of the ray tracheids. Further, the total uniseriate ray parenchyma cell height was slightly greater in QCI with also a greater number of the ray parenchyma cells, although the differences were not statistically significant. This was reflected in the uniseriate ray tissue height which was additionally greater in QCI without being significant. In spite of this, it is possible that the greater amount of ray tracheid and ray parenchyma tissue may contribute to greater fluid flow in the radial direction as observed by earlier workers, i.e. ray parenchyma cells (Wardrop and Davies, 1961; Krahmer and Cote, 1963; Hayashi and Kishima, 1965), and the ray tracheids (Buro and Buro, 1959; Liese and Bauch, 1967).

Ray Tracheid Cells

As mentioned by Greaves (1974), ray parenchyma cells including ray tracheids are much better treated than longitudinal tracheids. In addition to this, Liese and Bauch (1967) also stated that the relatively small proportion of ray tracheids is the main reason for the limited radial penetration of spruce (*Picea abies*). Ray tracheids have unaspirated bordered pits even when air dry (Baines and Saur, 1985), thus the ray tracheids surrounding the ray parenchyma cells are often more penetrated by the preservative, while the ray parenchyma cells are less penetrated (Baines, 1986).

All of these above explanations fit the findings of the present study on Sitka spruce. The variation of ray tracheid height, average number and diameter of the ray tracheid bordered pits appeared to be more important factors in determining the possible fluid uptake in radial direction. In this case, the average number of the bordered pits in ray tracheid height was more numerous in SO than in QCI whereas the diameter of ray tracheid bordered pits was notably larger in QCI compared to SO. Given this, it could be inferred that the greater ray tracheid height may result in a greater number of the bordered pits per ray tracheid cell while the diameter of the ray tracheid bordered pit is considerably smaller. As pointed out, earlier pore radius has a pronounced effect on fluid flow.

Lateral redistribution from penetrated axial tracheids to ray tracheids via bordered pit pairs may depend upon the degree of pit aspiration and the strength of seal in the aspirated pits (McQuire, 1970). In this case, when unsealed blocks of all seed origins were vacuum impregnated for density determinations it was found that QCI was the slowest to sink but in pressure impregnation for permeability determinations it had much greater uptakes than the other seed origins particularly in the radial direction. This may suggest that if a large proportion of these bordered pits are aspirated the membrane is easily ruptured or displaced by pressure, and this interruption may improve uptake radial penetration.

Further fluid transport may occur between the ray parenchyma cells and ray tracheids (Siau, 1984) through either semi-bordered pits or simple pits which also permit flow to adjacent ray parenchyma cells. In this study, the width of both ray parenchyma cells and ray tracheids were found to be notably wider in QCI than in SO while the diameter of both semi-bordered and simple pits between the ray parenchyma cells and ray tracheids were rather smaller in SO compared to QCI. The smaller diameter of both semi-bordered and simple pits would increase resistance to fluid flow between the ray parenchyma cells and ray tracheids in SO. Conversely, the larger semi-bordered and simple pits between the ray parenchyma cells and ray tracheids in QCI could also be important for greater radial flow.

Cross-field Pits

The uniseriate rays were also examined by SEM in RLS to determine the number of ray parenchyma cross-field pits per axial tracheid cross-field, their dimensions and the changes in dimensions across growth rings. This was justified because there is some evidence that some of the radial flow of fluids is through the ray parenchyma cells and between the longitudinal tracheids and ray parenchyma cells via cross-field pits (Siau, 1984).

There were major differences in the nature of cross-field pits between the two different selected seed origins. The most important of these were the differences between the earlywood and latewood pit diameters in the two seed origins. For instance, in the less permeable SO, the earlywood cross-field pits along the ray parenchyma cells were more numerous and significantly larger than in QCI, although the latewood cross-field pits in SO were much smaller and less numerous than those of QCI. Moreover, the changes in mean cross-field pit diameters across transects of latewood and earlywood show considerable variation in QCI with a slight systematic increase in the middle of the growth rings. However, the latewood variation in SO is low compared to the earlywood variation and there is an abrupt transition zone at the growth ring boundary.

Therefore, cross-field pits with greater diameter and variations between latewood or earlywood allows greater radial flow between the ray parenchyma cells and axial tracheids.

Ray Parenchyma Cell Ends: End Platform

The ray parenchyma cell ends (end platform), and of the simple pits in the uniseriate ray tissue also appeared to vary significantly between the seed origins. The end platform was longer and thicker in SO and the diameter of the simple pits in SO was almost half that of those in QCI. Therefore, the thinner end platform and the larger diameter of the simple pits in QCI may increase fluid movement along the ray parenchyma if ray parenchyma flow occurs. Liese and Bauch (1967) and Behr *et al.* (1969) suggest that the passage of fluid between the two ray parenchyma cells was evidence of flow through simple pit pairs despite their small size (a few microns in diameter) and a separating membrane through which only very small plasmodesmata lead. However, as no other investigations exist as to the variation of radial flow along the ray parenchyma cells via the simple pits in Sitka spruce, the result of this investigation has to be tested and further evidence is needed to confirm this hypothesis.

6.4.2 Fusiform Ray Tissue

In fusiform rays, similar features to those examined in uniseriate ray tissue were also examined by light microscopy in TLS. These included the height, width and diameter of the resin canal, and the number of the epithelial cells around the resin canal and their dimensions. Fusiform ray tissue showed some similar characteristics to the uniseriate ray tissue, i.e. that QCI had a greater amount of the fusiform ray tissue, more numerous and larger ray parenchyma cells than SO. The differences in the amount of the fusiform ray tissue were statistically significant, although both the total height of the ray parenchyma cells and the ray tracheids were not significant.

Resin Canals and Epithelial Spaces

The dimensions of both resin canals and epithelial cells were significantly greater in the most radially permeable seed origin QCI (Rhondda) having larger diameter the resin canals (some 3x larger) and larger diameter epithelial cells (some 2x larger) and more intercellular spaces in comparison to the least radially permeable seed origin SO (Dalby). Erickson (1970) and

Nicholas and Siau (1973) have stated that the presence of resin canals, epithelial cells and intercellular spaces have a recognisable influence on the radial flow and penetration.

6.5 Conclusions

The principal objective of this chapter was to recognise and understand the structural features (both direct and indirect) which influence the fluid flow in the radial direction of Sitka spruce by examination of most (QCI, Rhondda) and the least (SO, Dalby) radially permeable samples.

Analyses of the data collected during the course of this study suggest that both ray parenchyma cells and ray tracheids (in either uniseriate or fusiform ray tissues) offer the major flow path in the radial direction. In consequence therefore, the radial flow of fluid:

1-) is probably through the ray parenchyma cells to the longitudinal tracheids across cross-field pit apertures and then back again to the other ray parenchyma cells.

2-) is facilitated by bordered pits leading from longitudinal tracheids to ray tracheids and then either semi-bordered or simple pits permitting flow to adjacent ray parenchyma cells.

3-) may occur through simple pit pairs from ray parenchyma cell to ray parenchyma cell.

4-) may also occur through resin canals and associated intercellular spaces.

7 General Discussion and Conclusions

7.1 General Discussion

The variations in density, longitudinal and radial permeability (i.e. the percentage of void volume filled) of Sitka spruce have been investigated between the eight seed origins extending from north to south of its natural distribution that planted in UK.

7.1.1 The Seed Origins Sampled, and Trial Sites

The study was carried out on 80 twenty year old trees from eight seed origins (Alaska, British Colombia, Queen Charlotte Islands, North Washington, South Washington, North Oregon, South Oregon, California) of Sitka spruce grown in two experimental sites at Rhondda in South Wales and at Dalby in North-East England.

All the trees were sampled from the IUFRO seed origin trial planted in 1975. Emphasis on the collection process was basically given to the eight seed origins from throughout the whole distribution of the species from north to south since these give adequate cover of the natural range and of the range of sites on which this species is used in Britain. The decision to use these particular origins was also based on the similarities of latitude and climatic and ecological conditions between Britain and the selected seed origins.

7.1.2 Collection and Preparation of Experimental Samples

To collect adequate information about the influences of the tree diameter, ring width and latewood proportion on both density and permeability, and also density on permeability, five trees of the eight seed origins (a total of 40 trees from each site) were selected.

A pilot experiment was initially run to determine the suitable impregnation parameters. Difficulty with machining to ensure orientation of rays and growth rings was encountered with the rectangular samples, so instead cylindrical plug samples (30 x 15 mm diameter) were prepared. This allowed the production of many samples to a dependable standard. Subsequently, felled trees were sampled with sufficient replication in sapwood at 1.3, 2.3 and 3.3 m above ground level to allow statistical analysis of density and treatment results.

7.1.3 Determination of Density

Density was determined by the maximum moisture content method using thin samples (3x15 mm diameter) taken from longitudinal plug samples. Longitudinal density samples (LDS) shorter in the tracheid longitudinal axis (fiber direction) and are thus easier to saturate. The LDS were soaked in deionised water in the vacuum desiccator for 10 days.

It was concluded that to determine the density of Sitka spruce, the shorter block length (3 mm longitudinal direction) and the longer impregnation time (10 days) proved to be the most reliable method.

7.1.4 Determination of Growth Ring Width

Although the proportion of latewood (Lw%) to earlywood is a further factor influencing wood density due to a high correlation between latewood percentage and density, a microscopic determination for the Lw% on each experimental sample was not made due to insufficient time.

7.1.5 Determination of Permeability

Longitudinal and radial permeability was measured by a full-cell process using different treatment schedules for radial and longitudinal plug samples because of the anisotrophy of flow. Therefore, suitable schedules for radial and longitudinal flow directions were determined in an initial trial experiment using locally grown Sitka spruce (3.6.1). The full cell trial schedules used were, initial vacuum: 15 minutes at -0.84 bar (640 mm Hg) and various pressure periods (Table 3.4). No final vacuum was applied.

The trial results generally showed that the fluid retention is, as expected, markedly greater in the longitudinal flow direction despite the shorter period and lower pressure to the longitudinal samples. The results also showed that the effect of time on retention was higher in the longer treatment time. The fluid retention (g/g) increased from 0.48 to 0.86 as the time increased from 3 to 9 min on longitudinal penetration, and increased from 0.10 to 0.38 with increasing of the time from 5 to 60 min on radial penetration.

From the experimental data, it was therefore concluded that the suitable treatment schedules should be -0.84 bar (640 mm Hg) initial vacuum for 15 minutes and various pressure periods according to the flow directions, i.e. 5 bar pressure for 45 minutes for the radial direction, and 3 bar pressure for 7 minutes for the longitudinal direction.

7.1.6 Experimental Results

Density

Density in mature wood of Sitka spruce was found to be slightly greater at breast height than higher in the tree, and this difference became more noticeable with increasing distance from breast height. Comparing the results of density at the different heights (1.3, 2.3 and 3.3 m), it appears that density declines with increasing height in the stem corresponding to a trend of increasing ring width from base to apex of the tree, and since these trends were common to all trees in both sites. It has also been found that wood density was more correlated with ring width in Rhondda than in Dalby accounting for 50.5 % and 38.0 % respectively.

The trees of NW, SW and NO in both sites, QCI and SO in Rhondda had the highest wood density due partly to their slower rates of growth, and CA in both sites had the lowest on account of its rapid volume growth. It was also found in this study that seed origins AL and BC grew poorly in both sites, it may be therefore suggested that these two seed origins should be avoided in the future plantations. Therefore, it suggested that QCI, NW, SW and NO should be selected for more plantations as all grew well producing reasonably high density.

Permeability

The experimental results showed that the wood permeability occurred differently in the two flow directions examined and inversely changed in each site. The general view of the trend showed that although they were less treated longitudinally, the trees of Rhondda were more treated radially as compared to those for Dalby.

The longitudinal permeability (LVVF%) was greatest at 2.3 m height although the radial permeability (RVVF%) was lowest in the centre (2.3 m) (Table 4.6, Figure 5.7 - 5.10). Thus, comparison of the overall means of both LVVF% and RVVF% suggests that there was a negative correlation between LVVF% and RVVF% at all the three heights from base to apex of the tree.

Since the trees from the seed origins QCI and NW in both sites had higher than average LVVF% and RVVF%, QCI and NW should be particularly planted to produce wood of adequate density and better permeability.

The results obtained in this study generally show that the seed origins QCI and NW, located in the central part of the natural distribution of Sitka spruce, had the greatest longitudinal permeability (LVVF%). Moreover, the greatest radial permeability (RVVF%) also occurred in both QCI and NW. Therefore, QCI was highlighted as an interesting seed origin. NO (longitudinally) and SO (radially) were the least treated seed origins at the lowered of permeability. It appears that there are reasonable explanations for differences in longitudinal permeability and that the differences are linked to density which is in current breeding programs. Furthermore, the major aspects of longitudinal permeability are associated to post-harvest processing, e.g. drying. Little is known however about radial permeability but differences seen in this study between QCI and SO were investigated further. Thus, the ray structure of these two seed origins was microscopically examined and several different patterns of radial penetration were observed.

Anatomical Analysis

Emphasis on anatomical analysis was given to the result of the percentage of void volume filled by preservative radially. This was the greatest in tree 1 (had a narrowest dbh) of QCI of Rhondda and was the lowest in tree 4 (had a second largest dbh) of SO of Dalby.

Measurement of height and width of both ray parenchyma and ray tracheid cells in either the uniseriate or the fusiform ray tissues and their cell wall thickness, height and width of both resin canals and epithelial cells (with also the intercellular spaces) in fusiform ray tissue were carried out using a monochrome Image Analysis System (SIA). The use of the light microscope has to some extent been superseded in the study of wood anatomy of Sitka spruce by the SEM (Scanning Electron Microscope) which was particularly used for examining the cross-field pits in QCI and SO since the condition of pit membranes and size of the apertures was determined easily by examining the radial-longitudinal surfaces.

The total height of the ray tracheids was significantly greater in the more radially permeable QCI. The total uniseriate ray parenchyma cell height was also slightly greater in QCI with a greater number of the ray parenchyma cells, although the differences were not statistically significant. This was reflected in the uniseriate ray tissue height which was additionally greater in QCI without being significant. In this study, the width of both ray parenchyma cells and ray tracheids were also found to be notably wider in QCI than in SO while the diameter of both semi-bordered and simple pits between the ray parenchyma cells and ray tracheids were rather smaller in SO compared to QCI. The smaller diameter of both semi-bordered and simple pits would increase resistance to fluid flow between the ray parenchyma cells and ray tracheids in SO.

There were also major differences in the nature of cross-field pits between the two different selected seed origins. The most important of these were the differences between the earlywood and latewood pit diameters in the two seed origins. For instance, in the less permeable SO, the earlywood cross-field pits along the ray parenchyma cells were more numerous and significantly larger than in QCI, although the latewood cross-field pits in SO were much smaller and less numerous than those of QCI. Moreover, the changes in mean cross-field pit diameters across transects of latewood and earlywood show considerable variation in QCI with a slight systematic increase in the middle of the growth rings. However, the latewood variation in SO is low compared to the earlywood variation and there is an abrupt transition zone at the growth ring boundary.

Therefore, it is stated that the major problems in the treatment of spruce radially relate to the anatomical structure of the material. The most important morphological features influencing this was the amount nature and condition of both the ray tracheids and the ray parenchyma cells, and the cross-field pits in particular.

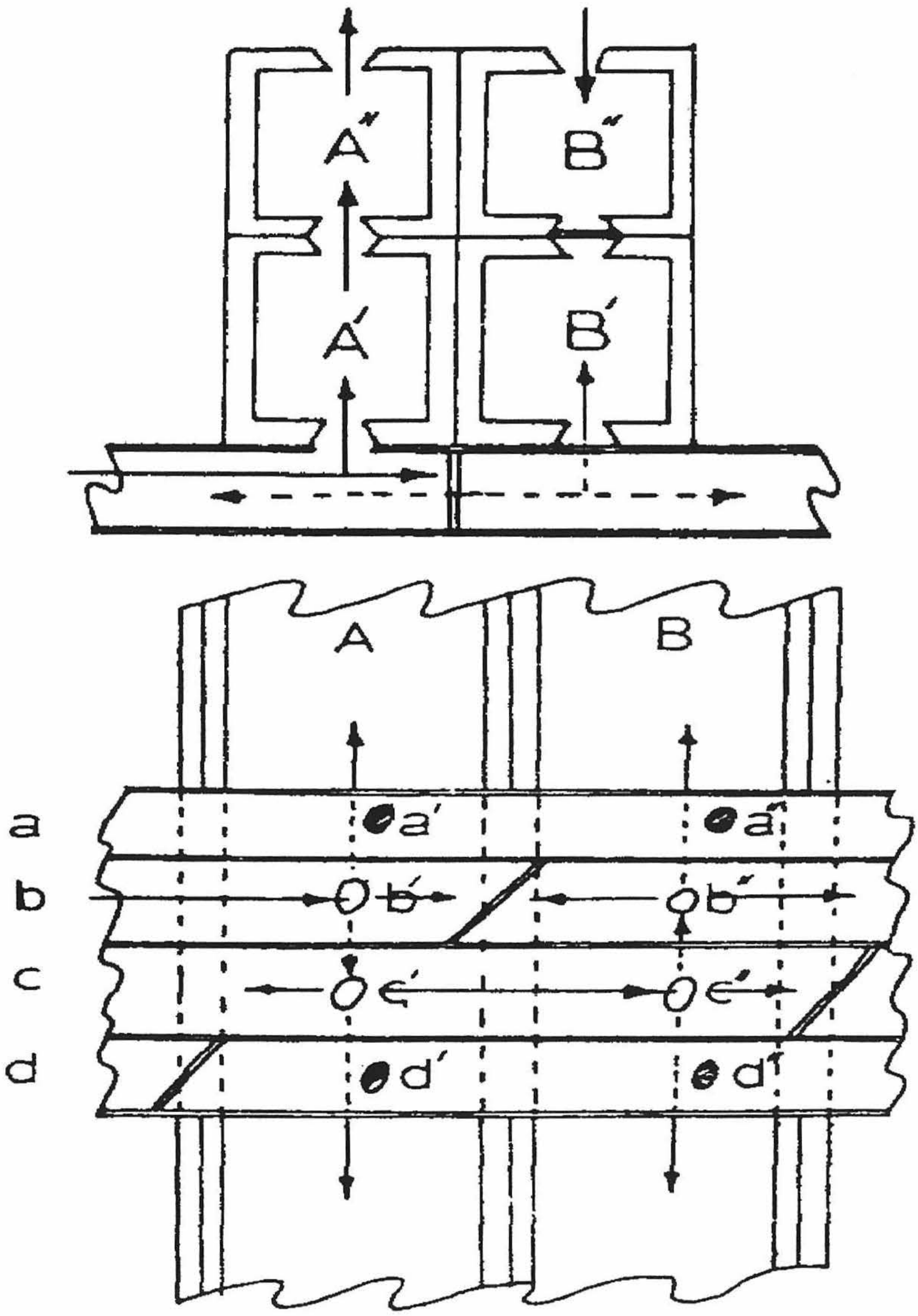
The Proposed Model for the Radial Flow of Sitka Spruce

The mechanism for radial flow that was proposed in Sitka spruce might be as shown in Figure 7.1;

The liquid passing along ray parenchyma cell b is impeded by the end wall of that cell and pressure builds up. At a certain point the membrane covering cross-field pit b' ruptures, and the liquid flows into axial tracheid A.

When this is filled and pressure again builds up cross-field pit c' is ruptured and flow is initiated in both directions in ray parenchyma cell c.

From here, penetration of tracheid B can be effected when the membrane of c" is ruptured and finally the liquid can re-gain entry to parenchyma cells of row b by rupturing the membrane at b".



A and B = axial tracheid, a and d = ray tracheid, a' a" and d' d" = bordered pit, b and c = ray parenchyma cell, b' , b" and c' , c" = cross-field pit

Figure 7.1. Diagrammatic representation of TS and RLS showing *Podocarpus* type flow which is the proposed model for the radial flow of Sitka spruce (after McQuire, 1970).

Analyses of the data collected during the course of this study suggest that both ray parenchyma cells and ray tracheid (in either uniseriate or fusiform ray tissues) offer the major flow path in the radial direction. In consequence therefore, the radial flow of fluid:

(1) is probably through the ray parenchyma cells to the longitudinal tracheids across cross-field pit apertures and then back again to the other ray parenchyma cells,

(2) is associated by bordered pits leading from longitudinal tracheids to ray tracheids and then either semi-bordered or simple pits permitting flow to adjacent ray parenchyma cells,

(3) is conducted by simple pit pairs from ray parenchyma cell to ray parenchyma cell,

(4) is also through resin canals and intercellular spaces.

7.2 Conclusions

This study includes work on density and both longitudinal and radial permeability. Much of the work on density and permeability has already been reported (Chapter 4) and discussed (Chapter 5), and the novel work in this study is on the variation in radial permeability of trees from different seed origins and its explanation (Chapter 6). Accordingly, density and permeability conclusions are listed separately.

7.2.1 Density

1) Lower density was accompanied by increased growth rate (ring width). Consequently, the slower grown mature wood of the Rhondda trees had higher density than that of the faster grown Dalby trees.

2) With vertical variation, density was found to be slightly greater at breast (1.3 m) height than higher in the tree, and this difference became more noticeable with increasing distance from breast height, i.e. it appears that density at the different heights (1.3, 2.3 and 3.3 m)

declines with increasing height up the stem corresponding to a trend of increasing ring width with decreasing latewood proportion from base to apex of the tree.

3) Between sites, there were also differences up the tree. The rate of decline in density was coupled with an increase of ring width; this appeared to be related to the decrease in latewood proportion more in Rhondda than in Dalby. In Dalby, the trees had less taper but had a larger diameter. The variation of tree diameter with density showed systematic patterns of increase with decreasing tree height in Rhondda although this was different in Dalby. Hence the variations of ring width against density were greater at all the levels in Rhondda in comparison to Dalby.

4) For between tree variation, density in Sitka spruce was less closely correlated with ring width. The variation in mean ring width only accounted for 27.3 per cent. Wood density was more correlated with ring width in Rhondda than in Dalby accounting for 50.5 % and 38.0 % respectively. Tree diameter (20.1 %) also accounted for little variation in density. This was only between the trees of Dalby with relatively narrow ring width.

5) Within each site, trees of NW, SW and NO in both sites, SO in Rhondda, AL in Dalby had higher than average mean densities, and trees of BC and CA in both sites, AL in Rhondda, QCI and SO in Dalby had a lower than average density. However, only the trees of NW, SW and NO seed origins in both Rhondda and Dalby and also QCI and SO in Rhondda were with average growth rates for their sites. It was stated that the trees of NW, SW and NO in both sites, QCI and SO in Rhondda had the highest wood density due partly to their slower rates of growth (ring width), and CA in both sites had the lowest on account of its rapid growth. Therefore, it was concluded that the trees of QCI, NW, SW and NO may be identified as favourable genotypes to produce wood of the desired density quality.

6) The outer growth rings of the Dalby trees were significantly narrower probably due to increased competition between the trees. However, the density of the outer rings examined was significantly higher in the Rhondda trees. This was associated with narrower tracheids across growth rings from earlywood to latewood. Between the seed origins of these two sites, significant differences were evident in ring width.

7) There were significant differences between seed origins and the interaction seed origin x site. The trees of seed origins CA and SO (Dalby) were found to grow much faster than would be expected from their latitude of origin, while those from the mainland of BC (Dalby) were much less vigorous than would be expected from a simple cline with latitude.

7.2.2 Permeability

1) The LVVF% varied vertically within trees and was generally found to be higher at the centre (2.3 m) of the tree than either at breast (1.3 m) or top (3.3 m) heights of the tree. The results showed increase LVVF% from 1.3 m to the 2.3 m, and a decreasing after 2.3 m to 3.3 m.

The highest value of LVVF% at 2.3 m was accompanied by moderate density and narrow ring widths. Thick-walled latewood cells are likely to have fewer aspirated bordered pits which would assist penetration.

The lowest LVVF% at the 3.3 m height could also be associated with wider ring widths and less latewood. Greater proportions of earlywood would tend to mitigate against high permeability as a result of pit aspiration. Also juvenile wood would be expected to be greatest at this point. Juvenile wood has shorter narrower tracheids which could be expected to show lower LVVF% characteristics.

2) Within the trees of Dalby, ring width accounted for more of the variation in LVVF% than tree diameter but neither of these were significantly correlated in Rhondda. On the other hand, both latewood proportion and density were significantly correlated with LVVF% in both sites. This was much more important in Dalby. It could be said from this result with the Dalby trees that low density supplied sufficient space to accommodate the a greater volume of preservative.

3) Similarly with between tree variation, a high LVVF% was associated with higher volume (growth rate) (Dalby) due to a greater porosity which was accompanied by lower density.

Consequently, the faster grown mature wood of the Dalby trees had a greater LVVF% than in the slower grown Rhondda trees.

4) The percentage of void volume filled was notably different in the radial and the longitudinal directions. In each site, the order was reversed. In general, the trees of Dalby were more treated longitudinally when compared to trees of Rhondda, although they were less treated radially. On the other hand, QCI had very high radial and longitudinal permeability in both sites. This could be explained by interconnection between the different flow pathways of the different directions. However, this was not a valid observation for all of the seed origins, may not be the actual reason in Sitka spruce, e.g. in SO where the RVVF% was the lowest among the others while its LVVF% was the second highest.

5) The results obtained in this study generally show that the overall means for LVVF% for the seed origins QCI (63.9) and NW (63.9) which are located in the central part of the natural distribution of Sitka spruce had the greatest longitudinal permeability. This is in contrast to NO (50.9) which is located in the south. Moreover, the greatest radial permeability by means of RVVF% also occurred in both QCI (24.6) and NW (19.7) in comparison to SO which is located in the south (14.8).

Therefore, it may be suggested that the trees from the seed origins QCI and NW should be particularly planted to produce wood of adequate density and better permeability.

7.3 Future Work

It has not been fully possible with the wood specimens used to fully separate at the contributions made to flow by ray tracheids, ray parenchyma and resin canals.

1. Further study is required to investigate the radial flow path using a direct microscopic observation system. Direct observation of fluid moving in wood would also reveal important detail on fluid flow and preferred pathways. Such a study could be done in a specially designed flow cell with transparent walls but previous attempts at this have failed due to leakage around sealants in the flow cell (Dinwoodie, pers comm.).

2. A different approach to a direct observation system could be done by inserting microcapillaries into the wood cells and applying fluid to individual cells. This system would not only allow direct observation of fluid flow but also pressures could be applied. If different pressures could be applied then the resistance of different cells could be measured, not only between parenchyma cells but between, possibly, different seed origins.

3. An investigation of the actual flow path could be obtained staining with a copper locating dye and examination by image analyser and light microscopy might show the extent of ray penetration and cells treated. Alternatively, examination by transmission electron microscopy (TEM) at different stages of treatment might reveal important details concerning radial flow. The problem with this system might be that preservative will relocated during fixation. To eliminate this material could be rapidly frozen and examined frozen hydrated, by SEM / EDAX, a development of the work by Pendlebury *et al* (1991).

4. In studies of the radial permeability of different seed origins the structure of the ray pit membranes should be investigated by TEM to compare features such as membrane thickness, size and frequency of pores and plasmodesmata.

5. Studies done so far on microscopical analysis are limited to, effectively two pieces of wood. Further work should be done to confirm the results of chapter 6.

REFERENCES

AEBISCHER, D. P. (1995). Personal communication. University of Wales, *School of Agricultural and Forest Sciences*, Bangor.

ANDERSON, B. E. , GORTNER, R. A. and SCHMITZ, H. (1941). Factors affecting the decreasing rate of flow of liquids through wood. University of Minnesota, Agricultural Experiment Station, *Technical Bulletin*, 146 (70 pp).

ARSENAULT, R. D. (1973). Factors influencing the effectiveness of preservative systems. Preservatives and preservative systems, wood deterioration and its prevention by preservative treatments (ed. by Nicholas, D. D.), **2**: 121-178, *Syracuse University Press*, New York

BAILEY, I. W. (1913). The preservative treatment of wood, II. The structure of the pit membranes in the tracheids of conifers and their relation to the penetration of gases, liquids and finely divided solids into green and seasoned wood. *Forestry Quarterly*, **11**: 12-20.

BAILEY, P. J. (1964). The permeability of softwoods. *Journal of the Institute of Wood Science*, **12**: 44-55.

BAILEY, P. J. (1965). Some studies on the permeability of wood in relation to timber preservation. *Proceedings, British Wood Preservation Association*, **2**: 31-66,.

BAILEY, P. J. and PRESTON, R. D. (1969). Some aspects of softwood permeability (I). Structural studies with Douglas-fir sapwood and heartwood. *Holzforschung*, **23** (4): 113-120

BAILEY, P. J. and PRESTON, R. D. (1970). Some aspects of softwood permeability (II). *Holzforschung*, **24** (2): 37-45

BAINES, E. F. (1986). The current status of commercial waterborne preservative treatment of spruce. *Proceedings, British Wood Preservation Association*, 14-26.

BAINES, E. F. and SAUR, J. M. (1985). Preservative treatment of spruce and other refractory wood. *Proceedings, American Wood Preservation Association*, 81: 136-147.

BAMBER, R. K. and BURLEY, J. (1983). The wood properties of Radiata pine. *Commonwealth Agricultural Bureaux*, Slough (84 pp).

BAMBER, R. K. and FUKAZAWA, K. (1985). Sapwood and heartwood: a review. *Forestry Abstracts*, **46** (9): 567-580.

BANKS, W. B. (1970). Some factors affecting the permeability of Scots pine and Norway spruce. *Journal of the Institute of Wood Science*, **5** (1): 10-17.

BANKS, W. B. (1981) Addressing the problem of non-steady state liquid flow in wood. *Wood Science and Technology*, **15**: 171-177.

BARNETT, J. R. (1988). Microscopy of wood. *Microscopy and Analysis*, **4**: 11-13.

BEHR, E. A. , SACHS, I. B. , KUKACHKA, B. F. and BLEW, J. O. (1969). Microscopic examination of Pressure-treated wood. *Forest Products Journal*, **19** (8): 31-40

BENDTSEN, B. A. (1978). Properties of wood from improved and intensively managed trees. *Forest Products Journal,* **28** (10): 61-72.

BERGERVOET, A. J. (1984). A method for treating partially seasoned pine with CCA preservatives. *Proceedings, American Wood Preservers Association,* **80**: 90-96.

BLAND, M. (1995). An introduction to medical statistics. *Oxford University Press Inc.,* New York (396 pp).

BODIG, J. and JAYNE, B. A. (1982). Mechanics of wood and wood composites. *Van Nostrand Reinhold Co. Inc.* , New York (712 pp).

BOLTON, A. J. and BEELE, P. M. (1981). The applicability of orifice flow and drag theory to the axial flow of gases through conifer wood. *Wood Science and Technology,* **15**: 178-88

BOLTON, A. J. and PETTY, J. A. (1975). Structural components influencing the permeability of ponded and unponded Sitka spruce. *Journal of Microscopy,* **104** (1): 33-46.

BOLTON, A. J. and PETTY, J. A. (1978). A model describing axial flow of liquids through conifer wood. *Wood Science and Technology,* **12**: 37-48

BOLTON, A. J. and PETTY, J. A. (1977). Influence of critical point and solvent exchange drying on the gas permeability of conifer sapwood. *Wood Science,* **9** (4): 187-193.

BOSSHARD, H. H. and HUG, U. E. (1980). The anastomoses of the resin canal system in *Picea abies* (L.) Karst. , *Larix decidua* Mill. and *Pinus sylvestris* L. *Holz als Roh- und Werkstoff,* **38** (9): 325-328.

BRAMHALL, G. and WILSON, J. W. (1971a). Axial gas permeability of Douglas- fir micro-sections dried by various techniques. *Wood Science,* **3** (4): 223-230.

BRAMHALL, G. (1971b). The validity of Darcy's law in the axial penetration of wood. *Wood Science and Technology,* **5** (2): 121-134

BRAZIER, J. D. (1967). Timber improvement (I). A study of the variation in wood characteristics in young Sitka spruce. *Forestry,* **40** (2): 117-128.

BRAZIER, J. D. (1970). Timber improvement (II). The effect of vigour on young-growth Sitka spruce. *Forestry,* **43** (2): 135-150.

BRAZIER, J. D. (1972). Some observations on the wood of young provenances of Sitka spruce grown at Bush and Wykeham. Home Grown Timber Research Committee Paper 243. Forest Products Research Laboratory, Princes Risborough.

BRAZIER, J. D. (1975). Changing pattern of research in wood anatomy. *Journal of Microscopy,* **104** (1): 53-64.

BRAZIER, J. D. (1977). The effect of forest practices on quality of the harvested crop. *Forestry,* **50** (1): 49-66.

BREESE, M. C. (1990). The measurements of density. Teaching notes. *University of Wales, School of Agricultural and Forest Sciences,* Bangor (20 pp).

B. R. E. D. (1977). Wood preservatives: application methods. *Building Research Establishment Digest,* **201**.

BRIAND, C. H. , POSLUSZNY, U. and LARSON, D. W. (1993). Influence of age and growth rate on radial anatomy of annual rings of *Thuja occidentalis* L. *International Journal of Plant Sciences,* **154** (3): 406-411.

BROUGHTON, J. A. H. (1962). Properties of 30-37 year old Sitka spruce timber. D. S. I. R. Forest products Research Bulletin 48. HMSO, London.

BRUNDEN, M. N. (1964). Specific gravity and fiber length in crown formed and stem formed wood. *Forest Products Journal,* **14** (1): 13-17.

BS 4072 (1987). Wood preservation by means of copper/chromium/arsenic compositions. Part 2. Method for timber treatment. *British Standards Institution.*

BUCKMAN, S. J. , SCHMITZ, H. and GORTNER, R. A. (1935). A study of certain factors influencing the movement of liquids in wood. *Journal of Physical Chemistry,* **49** (1): 103-120.

BURO, A. and BURO, E. A. (1959). Contribution to the knowledge of how liquids penetrate into pine wood. Beitrag zur Kenntnis der Eindringwege fur Flussigkeiten in Kiefernholz. *Holzforschung,* **13** (3): 71-77.

BURR, H. K. and STAMM, A. J. (1947). Diffusion in wood. *Journal of Physical & Colloid Chemistry,* **L1**: 240-261.

BUTTERFIELD, B. G and MEYLAN, B. A. (1980). Three-dimensional structure of wood. An ultrastructural approach. 2nd edition. *Chapman and Hall.* London (103 pp).

BUTTERFIELD, B. G. , WALKER, J. C. F. , LANGRISH, T. A. G. , HARRIS, J. M. and

CHALK, L. (1951). Water and the growth of wood of Douglas fir. *Quarterly Journal of Forestry,* **45** (4): 237-242.

CHOONG, E. T. , TESORO, F. O. and SKAAR, C. (1966). Transverse air permeability of wood as an indicator of treatability with creosote. *Forest Products Journal,* **16** (3): 57-59.

CLAUSON, M. L. and WILSON, J. B. (1991). Comparison of video and x-ray for scanning wood density. *Forest Products Journal,* **41** (3): 58-62.

COMSTOCK, G. L. (1967). Longitudinal Permeability of Wood to Gases and Non Swelling Liquids. *Forest Products Journal,* **17** (10): 41-6

COMSTOCK, G. L. (1970) Directional permeability of softwoods. *Wood and Fiber,* **1** (4): 283-9

COMSTOCK. G. L. and W. A. COTE, J. R. (1968). Factors affecting permeability and pit aspiration in coniferous wood. *Wood Science and Technology,* **2** (4): 279-291.

COTE, W. A. and KRAHMER, R. L. (1962). The permeability of coniferous pits demonstrated by electron microscopy. *Tappi,* **45** (2): 119-122.

COTE, W. A. (1967). Wood ultrastructure: an atlas of electron micrographs. *University of Washington Press,* Seattle (33 pp).

CREBER, G. T. (1977). Tree rings: a natural data storage system. *Biological Review,* **52**: 349-383.

DAHLGREN, S. E (1975). Effect of pre-steaming on CCA treatment of spruce and redwood grown in southern Sweden. *Meddelande Svenska Traskyddsinstitutet*, **116** (21 pp).

DEGROOT, R. C. and KUSTER, T. A. (1986). SEM X-ray microanalysis of tracheid cell walls in southern yellow pine sapwood treated with water dispersible pentachlorophenol. *Wood and Fiber Science*, **18** (1): 58-67.

DELEPORTE, P. (1984). Results and methodology for the selection of Sitka spruce using several characteristics. *Annales de Reserches Silvicoles*, 1984: 282-337.

DENNE, M. P. (1979). Wood structure and production within the trunk and branches of *Picea sitchensis* in relation to canopy formation. *Canadian Journal of Forest Research*, **9**: 406-427.

DENNE, M. P. and DODD, R. S. (1980). Control of variation in wood quality within hardwood and softwood trees. IUFRO Division 5 conference, Oxford (pp 7-31).

DESCH, H. E. AND DINWOODIE, J. M. (1996). Timber: structure, properties, conversion and use. 7th edition. *MacMillan Press Ltd.* , London (306 pp).

DINWOODIE, J. M. (1963). Variation in tracheid length in *Picea sitchensis* Carr. *Forest Products Research*, Special Reports No 16 (55 pp).

DINWOODIE, J. M. (1975). Timber -a review of the structure- mechanical property relationship. *Journal of Microscopy*, **104** (1): 3-32.

DINWOODIE, J. M. (1981) Timber: its structure, properties and utilisation. 6th edition. *MacMillan Press Ltd*, London (410 pp).

DINWOODIE, J. M. , ILLSTON, J. M. and SMITH, A. A. (1990). Concrete, Timber and Metals. The nature and behaviour of structural materials. *Chapman and Hall Ltd.*, London (663 pp).

EATON, R. A. and HALE, M. D. C. (1993). *Wood: decay, pests and protection.* Chapman and Hall Ltd, London (546 pp).

ELLIOTT, G. K. (1960). The distribution of tracheid length in a single stem of Sitka Spruce. *Journal of the Institute of Wood Science*, **5**: 38-47.

ELLIOTT, G. K. (1966). Tracheid length and specific gravity distribution in Sitka spruce. *PhD Thesis*, University of Wales, Bangor.

EN 350 (1994). Durability of wood and wood-based products. Natural durability of solid wood. Part 2. Guide to natural durability and treatability of selected wood species of importance in Europe. *British Standards Institute.*

ERICKSON, H. D. , SCHMITZ, H. and GORTNER, R. A. (1938). Directional permeability of seasoned woods to water and some factors which affect it. *Journal of Agricultural Research*, **56** (10): 711-746.

ERICKSON, H. D. and SCHMIDT, R. N. (1969). Rupture of pit membranes during embedding procedures. *Wood Science and Technology*, **3** (3): 194-202.

ERICKSON, H. D. (1970). Permeability of southern pine wood - A review. *Wood Science*, **2** (3): 149-158.

ERICKSON, H. D. and BALATINECZ, J. J. (1964). Liquid flow paths into wood using polymerisation techniques, Douglas-fir and styrene. *Forest Products Journal*, **14** (7): 293-299.

ERICKSON, H. D. and CRAWFORD, R. J. (1959). The effects of several seasoning methods on the permeability of wood to liquids. *Proceedings, American Wood Preservation Association*, **55**: 210-220.

ERICKSON, H. D. and ESTEP, E. M. (1962). Permeability of Douglas fir heartwood from western Washington. *Forest Products Journal*, **12** (7): 313-324.

ERNST, F. K. B. (1964). The treatability of indigenous softwoods and hardwoods with coal-tar creosote. *Anstalt fur das Forstliche Versuchswesen*, **40** (2): 187-224.

EXLEY, R. R. , BUTTERFIELD, B. G. and MEYLAND, B. A. (1974). Preparation of wood specimens for the scanning electron microscope. *Journal of Microscopy*, **101**: 21-30.

FAULKNER, R. (1987). Genetics and breeding of Sitka spruce. Sitka spruce, *Proceedings, Royal Society of Edinburgh*, **93B**: 41-50.

FENGEL, D. (1970). The ultrastructure of cellulose from wood. *Wood Science and Technology*, **4**: 15-35.

FENGEL, D. and WEGENER, G. (1989) Wood: chemistry, ultrastructure, reactions. *Water de Gruyter*, Berlin (613 pp).

FIELDING, J. M. (1967). The influence of silvicultural properties on wood properties. *International Review of Forestry Research*, **2**: 95-126.

FINDLAY, W. P. K. (1975). Timber: Properties and Uses. *Granada Publishing Limited and Crosby Lockwood Staples*, London (224 pp).

FINDLAY, W. P. K. (1985) (ed.). Preservation of timber in the Tropics. *Forestry Sciences Series*, Dordrecht (273 pp).

FLEISCHER. H. O. (1950). An anatomical comparison of refractory and easily treated Douglas-fir heartwood. *Proceedings, American Wood Preservation Association*, **46**: 152-157.

FLETCHER, A. M. (1976). Seed collection in North-West America with particular reference to a Sitka spruce seed collection for provenance studies. IUFRO Sitka spruce international ten provenance experiment: nursery stage results, (2-20 pp).

FLETCHER, A. M. (1992). Breeding improved Sitka spruce. Super Sitka for the 90`s *Forestry Commission Bulletin*, **103**: 11-24.

FOGG, P. J. (1969). Longitudinal air permeability of four species of Southern pine wood. *Wood Science*, **2** (1): 35-43.

FORD-ROBERTSON, F. C. (1971). Terminology of forest science, technology practice and products. *Society of American Foresters*, Washington.

FORSYTH, P. G. and MORRELL, J. J. (1990). Hexavalent chromium reduction in CCA - treated sawdust. *Forest Products Journal*, **40** (6): 48-50

FRIES, A. (1986). Volume growth and wood density of plus tree progenies of *Pinus contorta* in two Swedish field trials. *Scandinavian Journal of Forest Research,* **1**: 403-419.

GILL, J. G. S. (1987). Juvenile-mature correlations and trends in genetic variances in Sitka spruce in Britain. *Silvae Genetica,* **36** (5/6): 189-194.

GOODCHILD, R. (1963). An instrument for sharpening Swedish type increment borers. *Commonwealth Forestry Review,* **42** (1): 16-18.

GORING, D. A. I. (1966). The structure of water in relation to the properties of wood constituents. *Pulp and Paper Magazine,* Canada, **64**: T517-T527.

GRAHAM, R. D. (1964). Sink-float test to determine treatability of Douglas-fir. *Forest Products Journal,* **14** (11): 516.

GREAVES, H. (1974). The Microdistribution of CCA in Preservative Treated Sapwood Using X-ray Microanalysis in Scanning Electron Microscopy. *Holzforschung,* **28**: 193-200

GREAVES, H. (1974). Electron probe X-ray analysis of selected anatomical structures in copper-chrome-arsenic treated wood. *Wood Science,* 7 (2): 164-168.

GREGORY, S. C. and PETTY, J. A. (1973). Valve action in bordered pits of conifers. *Journal of Experimental Botanic,* **24**: 763-767.

HALL, T. ECHLIN, P. and KAUFMANN, R. (1974). Microprobe analysis as applied to cells and tissues. *Academic Press, Inc.* , London.

HARADA, H. (1964). Further observation on the pit structure of wood. *Journal of Japan Wood Research Society,* **X**: 221-225.

HARADA, H. (1965). Ultrastructure and organisation of gymnosperm cell walls. Cellular ultrastructure of woody plants (ed. By W. A. Cote). *Syracuse University Press.*

HARDING, T. (1988). British softwoods: properties and uses. *Forestry Commission Bulletin,* **77** (41 pp).

HARRIS, J. M. (1954). Heartwood formation in Pinus radiata. *New Phytology,* **53** (3): 517-524.

HARRIS, J. M. (1969). The use of beta rays in determining wood properties 1. measurement of wood density and interpretation and interpretation of results. *New Zealand Journal of Forestry Science,* **12**: 409-418.

HARRIS, J. M. (1973). Physical properties, resin content and tracheid length of lodgepole pine grown in New Zealand. *New Zealand Journal of Forest Science,* **3** (1): 91-109.

HARRIS, A. S. (1980). Distribution, genetics and silvicultural characteristics of Sitka spruce. *Proceedings, IUFRO Joint Meeting of Working Parties,* Vancouver, **1**: 95-122.

HARTMAN, D. U. (1954). Untersuchungen uber die Durchlassigkeit des Holzes bei Druckfiltration, I. Durchlassigkeit fur Wasser. *Forstwissenschaftliches Centralblatt,* **73** (1/2): 40-63. (Canada Department of Forestry, Rural Development, Translation No 83).

HART, C. A. and THOMAS, R. J. (1967) Mechanism of Bordered Pit Aspiration as Caused by Capillarity. *Forest Products Journal*, **17** (11): 61-68

HARVALD, C. and OLESON, P. O. (1987). The variation of the basic density within the juvenile wood of Sitka spruce. *Scandinavian Journal of Forest Research*, **2**: 525-537.

HAYASHI, S. and KISHIMA, T. (1965a). Influence of resin canals upon the water permeability of wood. *Wood Research*, **35**: 25-32.

HAYASHI, S. and KISHIMA, T. (1965b). Study of the transverse penetration of water into softwood. *Wood Research*, **36**: 61-70.

HAYASHI, S. and NISHIMOTO, K. (1965) Studies on the Water Permeability of Hardwoods. *Wood Research*, **35**: 33-43.

HAYASHI, S. , NISHIMOTO, K. and KISHIMA, T. (1966) Study on the liquid permeability of softwoods. *Wood Research*, **36**: 47-57.

HAYGREEN, J. G. and BOWYER, J. L. (1982). Forest Products and Wood Science. An introduction. *The Iowa State University Press*, Ames, Iowa (495 pp).

HENRIKSSON, S. T. (1954). Wood impregnation by the method of alternating pressure. *Holz als Roh-und Werkstoff*, **12** (6): 233-241.

HENRIKSSON, S. T. (1958). Some experiments with oscillating pressure method of wood impregnation of New Zealand grown timber. *Proceedings, British Wood Preservation Association*, 154-168.

HOADLEY, R. B. (1980). Understanding wood. A craftman`s guide to wood technology. *The Taunton Press, Inc.* , London.

HOLT, D. B. , MUIR, M. D. , GRANT, P. R. and BOSWARVA, I. M. (1974). Quantitative Scanning Electron Microscopy. *Academic Press, Inc.* , London.

HOSLI, J. P. (1986). Fundamentals of testing wood permeability. *The International Research Group on Wood preservation*, IRG/WP/2248.

HOSLI, J. P. and FILION, M. (1983). Suitability of the pulsation process for the impregnation of white spruce round wood by creosote. *The International Journal of Wood Preservation*, **3** (1): 23-30.

HOSLI, J. P. and RUDDICK, J. N. R. (1988) Suitability of the pulsation process to pressure treat white spruce lumber with CCA. *Forest Products Journal*, **38** (6): 47-50

HOWARD, E. T. , and MANWILLER, F. G. (1969). Anatomical characteristics of southern pine stemwood. *Wood Science*, **2** (2): 77-86.

HUDSON, M. S and HENRIKSSON, S. T. (1956). The oscillating pressure method of wood impregnation. *Forest Products Journal*, **6** (10): 381-386

HUGHES, J. F. (1967). Density as an index of wood quality with special reference to the development of rapid and efficient methods of estimating density. Paper to Tropical Forestry Meeting, Commonwealth Forestry Institution, Oxford (4 pp).

HUNT, G. M. AND GARRATT, G. A. (1938) Wood Preservation. 2nd edition. *McGraw-Hill Book Company, Inc.* London (457 pp).

HUNT, G. M. AND GARRATT, G. A. (1967). Wood preservation. 3rd edition. *McGraw-Hill*. London

IIVESSALO, M. and PFÄFFLI, S. (1967). The structure of wood. Wood chemistry, 1st ed. Text Handbook. *Finland Paper Engineer Association*, (B_1-$B_1$52).

JAGELS,R. (1984). PEG-isothiocyanate procedures for assessing liquid movement in wood. *Pacific Regional Wood Anatomy Conference*, Tsukuba, Japan.

JANE, F. W. (1956). The structure of wood. 2nd edition. (revised by Wilson, K. and White, D. J. B.), *A and C Black*, London (427 pp).

JANE, F. W. (1970). The structure of wood (Ed. by Wilson, K. and White, J. B.). *Adam and Charles Black*, London.

JOHANSSON, I. and EDBERG, K. N. (1987). Studies on the permeability of Norway spruce. *The International Research Group on Wood Preservation*, IRG/WP/2295.

KANDEEL E. S. A. E. and BENSEND, D. W. (1969). Structure, density and shrinkage variation within a silver maple tree. *Wood Science*, **1**: 227-237.

KEITH, C. T. and COTE, W. A. (1968). Microscopic characterisation of slip lines and compression failures in wood cell walls. *Forest Products Journal*, **18** (3): 67-74.

KEITH, C. T. and CHAURET. G. (1988). Anatomical studies of CCA penetration associated with conventional (tooth) and with micro (needle) incising. *Wood and Fiber Science*, **20** (2): 197-208.

KELLOGG, R. M. and WANGAARD, F. F. (1969). Variation in the cell-wall density of wood. *Wood and Fiber*, **1**: 180-204.

KELSO, W. C. , GERTJEJANSEN, R. O. and HOSSFELD, R. L. (1963). The effect of air blockage upon the permeability of wood to liquids. University of Minnesota, Agricultural Experiments Station, St. Paul, *Technical Bulletin*, **242** (40 pp).

KELSO, W. C. , BARNES, H. M. and PARIKH, S. (1980). Effects of the MSU process and high preservative retentions on southern pine treated with CCA-type C. *Proceedings, American Wood Preservers Association*, **76**: 22-37.

KNUFFEL, W. E. (1985). The effect of CCA preservative treatment on the compression strength of South African pine structural lumber. *Holzforsch. Holzverwert*, **37** (5): 96-99.

KOCH, P. (1972). Utilisation of the southern pines. U. S. Department of Agriculture and Forest Service, *Agriculture Handbook*, **420**. 2.

KOLLMANN, F. F. P. and COTE, W. A. (1968). Principles of wood science and technology (I). Solid Wood. *Springer-Verlag*. Berlin (592 pp).

KORAN, Z. (1964). Air permeability and creosote retention of Douglas-fir. *Forest Products Journal*, **14** (4): 159-166.

KRAHMER, R. L. and COTE, W. A. (1963). Changes in coniferous wood cells associated with heartwood formation. *Tappi*, **46** (1): 42-49.

KRAUS, J. F. and LINES, R. (1976). Patterns of shoot growth, growth cessation and bud set in a nursery test of Sitka spruce provenance. *Scottish Forestry*, **30** (1): 16-24.

KUMAR, S. and JAIN, V. K. (1978). Effects of wood preservatives on physical properties of wood II. Effects of different salt loadings of copper-chrome-arsenic composition. *Wood and Fiber*, **9** (4): 262-269.

KUMAR, S. and MORRELL, J. J. (1989). Moisture content of western hemlock: influence on treatability with chromated copper arsenate Type C. *Holzforschung*, **43** (4): 279-280.

KURODA, N. and SIAU. J. F. (1988). Evidence of non-linear flow in softwoods from wood permeability measurements. *Wood and Fiber Science*, **20** (1): 162-169.

LADISLAV, J. K. (1985). Splitting wood specimens for observation in the scanning electron microscope. *Journal of Microscopy*, **142**: 71-77.

LANGRISH, T. A. G. and WALKER, J. C. F. (1993). Transport processes in wood. Primary wood processing, principles and practice (ed. by J. C. F. Walker). *Chapman and Hall Ltd.* , London.

LARSON, P. R. (1969). Wood formation and the concept of wood quality. *Yale University, School of Forestry*, Bulletin **74**.

LEE, S. J. (1990). Potential gains from genetically improved Sitka spruce. *Forestry Commission*, Research Information Note **190**. Forestry Commission, Edinburgh.

LEVI, M. P. , COUPE, C. and NICHOLSON, J. (1970). Distribution and Effectiveness in *Pinus* sp. of Water Repellent Additive for Water-borne Preservatives. *Forest Products Journal*, **20** (11): 32-7

LEWARK, S. (1986). Anatomical and physical differences between juvenile and adult wood. *Proceedings, 18th IUFRO World Congress*, Division **5**: 272-281.

LIESE, W. and BAUCH, J. (1966). Longitudinal permeability of green Silver-fir and Norway Spruce sapwood to organic solvents. *Holzforschung*, **20** (6): 169-74.

LIESE, W. and BAUCH, J. (1967a). On the Closure of Bordered Pits in Conifers. *Wood Science and Technology*, **1** (1): 1-13

LIESE, W. and BAUCH, J. (1967b). On anatomical causes of the refractory behaviour of spruce and Douglas-fir. *Journal of the Institute of Wood Science*, **19** (1): 3-14.

LIESE, W. and BAUCH, J. (1977). Investigations on the permeability of green sapwood of Norway spruce and Sitka spruce. *Holz als Roh-und Werkstoff*, **35** (7): 267-271.

LINES, R. (1980). The IUFRO experiments with Sitka spruce in Britain. *Proceedings, IUFRO Joint Meeting of Working Parties*, Vancouver, (1978) **2**: 211-225.

LINES, R. (1987). Choice of Seed Origins for the Main Forest Species in Britain. *Forestry Commission Bulletin*, **66**: 22-24.

LINES, R. and SAMUEL, C. J. A. (1987). Results of the IUFRO Douglas fir experiments in Britain at ten years. *Proceedings, IUFRO Meeting on Douglas-fir Provenances*, Vienna (1985).

MACLEAN, J. D. (1924). Relation of temperature and pressure to the absorption and penetration of zinc chloride solution into wood. *American Wood Preservation Association*, 44-73.

MACLEAN, J. D. (1927). Relation of treating variables to the penetration and absorption of preservatives into wood (III). Effect of temperature and pressure on the penetration and absorption of coal tar creosote into wood. *American Wood Preservation Association,* 53-64.

MAUN, K. W. (1992). Sitka spruce for construction timber: the relationship between wood growth characteristics and machine grade yields of Sitka spruce. *Forestry Commission,* Research Information Note **212.** Forestry Commission, Edinburgh.

McQUIRE, A. J. (1970). Radial permeability of timber. PhD Thesis, *University of Leeds,* (123 pp).

McQUIRE, A. J. (1975). Effect of wood density on preservative retention in fence posts. *New Zealand Journal of Forestry Science,* **5** (1): 105-109.

MEGRAW, R. A. (1985). Wood quality factors in loblolly pine. *Tappi Press.* Atlanta.

MITCHELL, A. (1982). Trees of Great Britain and northern Europe. *Collins, Sons & Co. Ltd,* London (288 pp).

MITCHELL, M. D. (1995). Variation of tracheid dimensions in relation to wood density of Sitka spruce. MPhil Thesis, *University of Wales,* Bangor (102 pp).

MITCHELL, M. D. and DENNE, M. P. (1997). Variation in density of *Picea sitchensis* in relation to within tree trends in tracheid diameter and wall thickness. *Forestry,* **70** (1): 47-60.

MORGAN, J. W. W. and PURSLOW, D. F. (1973) Physical and Chemical Aspects of Preservative Treatment by Non-pressure Methods. *Holzforschung,* **27** (5): 153-159.

MORRELL, J. J. (1987). A reddish purple stain of red alder by *Ceratocystis picea* and its prevention. *Forest Products Journal,* **37** (2): 18-20.

MURPHY, P. G. and PFEIFER, A. R. (1990). Wood density and branching characteristics of Sitka spruce provenances grown in Ireland. *Proceedings, IUFRO Joint Meeting of Working Parties,* Washington, 4-109.

NICHOLAS, D. D. (1972). Characteristics of preservative solutions which influence their penetration into wood. *Forest Products Journal,* **22** (5): 31-36.

NICHOLAS, D. D. (1973a). Wood deterioration and its prevention by preservative treatments. Vol 1. Degradation and protection of wood. *Syracuse University Press,* New York (380 pp).

NICHOLAS, D. D. (1973b). Wood deterioration and its prevention by preservative treatments. Vol 2. Preservatives and preservative systems. *Syracuse University Press,* New York (402 pp).

NICHOLAS, D. D. , PRESTON, A. F. AND ROWELL, R. M. (1983). Interaction of preservatives with wood. The chemistry of solid wood. *Proceedings, 185th Meeting of the American Chemical Society,* Seattle, 207: 307-320.

NICHOLAS, D. D. and SIAU, J. F. (1973). Factors Influencing Treatability of Wood (ed. by D. D. Nicholas) Vol. 2. Preservatives and Preservative Systems.

NICHOLAS, D. D. and COCKCROFT, R. (1982). Wood preservation in the USA. *STU,* Information No 288, Stockholm (129 pp).

NILSSON, T. and DANIEL, G. F. (1992). On the use of % weight loss as a measure for expressing results of laboratory decay experiments. *International Research Group on Wood Preservation,* Document No: IRG/WP/2394-92.

O`BRIEN, T. P. and McCULLY, M. (1981). The study of plant structure: principles and selected methods. *Termarcarphi Pty Ltd,* Australia.

OLESEN, P. O. (1971). The water displacement method. A fast and accurate method of determining the green volume of wood samples. *Forest Tree Improvement,* **3**: 1-23.

OLESEN, P. O. (1977). The variation of the basic density level and tracheid width within the juvenile and mature wood of Norway spruce. *Forest Tree Improvement,* **12**.

OSNACH, N. A. (1961). The permeability of wood. *Derev. Prom.* **10** (3): 11-13. (*Canada Department of Forestry and Research Development*, Translation No 99).

OSUSKY, A. , PRESTON, A. F. , FUKUDA, K. and PIZZI, A. (1982). Wood protection. *Proceedings, XVII IUFRO World Congress*, Kyoto, Division **5**: 293-330.

PANSHIN, A. J. , DE ZEEUW, C. and BROWN, H. P. (1964). Text Book of Wood Technology. Vol. 1. *McGraw-Hill Book Company Inc.*, New York (643 pp).

PANSHIN, A. J. , and de ZEEUW, C. (1980). Textbook of wood technology. 4th edition. *McGraw-Hill Book Co.*, New York (728 pp).

PARHAM, R. A. and GRAY, R. L. (1984). Formation and structure of wood. *Advances In Chemistry Series*, **207**: 3-56

PEARSON, R. G. and GILMORE, R. C. (1980). Effect of fast growth on the mechanical properties of loblolly pine. *Forest Products Journal,* **30** (5): 47-54.

PENDLEBURY, A. J., COETZEE, J., SORFA, E. and BOTHA, A. (1991). A new technique to determine solvent penetration in wood. *Holzforschung*, **45** (3): 205-208.

PETTY, J. A. (1970a). Permeability and structure of the wood of Sitka spruce. *Proceedings, Royal Society,* **B175** (1039): 149-166.

PETTY, J. A. (1970b) The relation of wood structure to preservative treatment. The wood we grow, *Society of Forestry Britain,* 29-35, *University Press,* Oxford.

PETTY, J. A. (1972). The aspiration of bordered pits in conifer wood. *Proceedings, Royal Society of London,* **B181** (1065): 395-406.

PETTY, J. A. (1975). Relation between immersion time and absorption of petroleum distillate in a vacuum-pressure process. *Holzforschung*, **29**: 113-8

PETTY, J. A. (1978). Effects of solvent-exchange drying and filtration on the absorption of petroleum distillate by spruce wood. *Holzforschung*. **32** (2): 52-55.

PETTY, J. A. and PRESTON, R. D. (1968). Electron probe microanalysis of metals in cell walls of conifer wood treated with preservatives. *Holzforschung,* **22**: 174-7

PETTY, J. A. and PRESTON, R. D. (1969). The removal of air from wood. *Holzforschung,* **23** (1): 9-15.

PETTY, J. A. and PURITCH, G. S. (1970). The effects of drying on the structures and permeability of the woods of *Abies grandis*. *Wood Science and Technology,* **4** (2): 140-154

PEYRESAUBES, R. (1985). Report on some research by the WEI on incising of refractory timbers as an aid to effective preservation. *Western European Institute for Wood Preservation*, Brussels.

PHILIP, M. S. (1994). Measuring trees and forests. 2nd edition. *CAB International.* Oxon.

PHILIPSON, W. R. , WARD, J. M. and BUTTERFIELD, B. G. (1971). The vascular cambium: its development and activity. *Chapman and Hall*, London (182 pp).

PHILLIPS, E. J. (1933). Movement of the pit membrane in coniferous woods, with special reference to preservative treatment. *Forestry*, **7**: 109-120.

PHILLIPS, E. J. (1948). The identification of softwoods by their microscopic structure. *Forest Products Research*, Bulletin **22**.

POLGE, H. (1966). Two examples of the use of curves for wood-density variation in studies of tree physiology. *Memorial Society of Botany*, 1968: 123-128.

PRATT, G. H. (1986). Timber drying manual. 2nd ed. (revised by CHL Tumun). *Building Research Establishment Report,* Aylesbury (152 pp).

PRESTON, R. D. (1974). The physical biology of plant cell walls. *Chapman and Hall*, London (491 pp).

PURSLOW, D. F. (1974). Methods of applying wood preservatives. *H.M. Stationery Office* London (26 pp).

RICHARDSON, B. A. (1978). Wood Preservation. 1st edition. *Construction Press.* Lancaster (278 pp).

RICHARDSON, B. A. (1993). Wood preservation. 2nd edition. E & FN Spon. *Chapman and Hall*, London (226 pp).

RUTH, R. H. (1958). Silvicultural characteristics of Sitka spruce. *USDA Forest Service, Pacific NW Forest and Range Experimental Station*, Silvical Series No 8 and 19.

SARANPAA, P. (1994). Basic density, longitudinal shrinkage and tracheid length of juvenile wood of *Picea abies* (L.) *Karst. Scandinavian Journal of Forest Research,* **9**: 68-74.

SARGENT, J. W. and PAGE, D. H. (1965). Ultra-thin sections of softwood tracheids and paper. *Nature*, **207** (4993): 217-218.

SAVILL, P. S. (1991). The silviculture of trees used in British forestry. *CAB International,* Wallingford (143 pp).

SAVILL, P. S. (1992) (ed.). Report of the 9th meeting of the national hardwoods programme, *Oxford Forestry Institute*, Occasional Papers **41** (51 pp).

SCARAMUZZI, G. (1965). The relationships of fibre wall thickness, fibre diameter and percentage of summer wood to specific gravity. *Presented at meeting of IUFRO.* Section 41. October 1965.

SCHULTZE-DEWITZ, G. W. (1965). Variation in cell diameter and cell wall thickness within and between trees of north coniferous species. *Presented at meeting of IUFRO.* Section 41. October 1965.

SCHULZE, B. and THEDEN, G. (1950). Penetration of wood preservatives. *Holzforschung,* **4** (3/4): 79-107.

SEBASTION, L. P. , W. A. COTE, J. R. and SKAAR, C. (1965). Relationship of gas phase permeability to ultrastructure of white spruce wood. *Forest Products Journal*, **15** (9): 394-404.

SIAU, J. F. (1970) Pressure Impregnation of Refractory Woods. *Wood Science*, **3** (1): 1-7

SIAU, J. F. (1971). Flow in Wood. *Syracuse University Press*. London (131 pp).

SIAU, J. F. (1972). The Effects of Specimen Length and Impregnation Time Upon the Retention of Oils in Wood. *Wood Science*, **4** (3): 163-70

SIAU, J. F. (1984). Transport processes in wood. *Springer-Verlag*. Berlin (245 pp).

SIAU, J. F. and SHAW, J. S. (1971). The Treatability of Refractory Softwoods. *Wood and Fiber*, **3** (1): 1-12

SIMPSON, H. L. (1993). Silvicultural influences on production and properties of juvenile wood in Sitka spruce. MPhil Thesis, University of Wales, Bangor (67 pp).

SIMPSON, H. L. and DENNE, M. P. (1997). Variation of ring width and specific gravity within trees from unthinned Sitka spruce spacing trial in Clocaenog, North Wales. *Forestry*, **70** (1): 31-45.

SJOSTROM, E. (1993). Wood Chemistry. Fundamentals and applications. 2nd edition. *Academic Press, Inc.* , London (293 pp).

SKAAR, C. (1972). Water in wood. *Syracuse University press*, New York (218 pp).

SMITH, D. M. (1954). Maximum moisture content method for determining specific gravity of small wood samples. *U. S. Forest Service, F. P. L.* Report No 2014.

SMITH, D. N. (1963). The permeability of wood to liquids and gases. Paper to FAO, 5th Conference on Wood Technology. *Forest Products Laboratory*, Wisconsin.

SMITH, D. N. and LEE, E. (1958). The longitudinal permeability of some hardwoods and softwoods. *Forest Products Research*, Special Report 13. HMSO, London.

SMITH, D. N. and BANKS, W. B. (1970). The mechanism of flow of gases through coniferous wood. *Proceedings, Royal Society of London*, **B 177** (1047): 197-223.

SMITH, W. B. (1986). Treatability of several north-eastern species with chromated copper arsenate wood preservative. *Forest Products Journal*, **36** (7/8): 63-69.

SPOLEK, G. A. and PLUMB, O. A. (1981). Capillary pressure in softwoods. *Wood Science and Technology*, **15** (3): 189-199.

SPURR, S. H. and HSIUNG, W. Y. (1954). Growth rate and specific gravity in conifers. *Journal of Forestry*, **52** (3): 191-200.

STAMM, A. J. (1946). Passage of liquids, vapours and dissolved materials through softwoods. *U. S. Department of Agriculture*, Teaching Bulletin **929**.

STAMM, A. J. (1959). Bound water diffusion into wood in the fiber direction. *Forest Products Journal*, **9** (1): 27-32.

STAMM, A. J. (1963). Permeability of wood to fluids. *Forest Products Journal*, **13** (11): 503-507.

STAMM, A. J. (1964). Wood and Cellulose Science. *Ronald Press Company*. New York (549 pp).

STAMM, A. J. (1970) Maximum effective pit pore radius of the heartwood and sapwood of six softwoods affected by drying and soaking. *Wood and Fiber,* **1** (4): 263-269

STAMM, A. J. (1975). Solid modified woods. Principles of wood science and technology (II). Wood based materials (ed. by Kollmann, F. F. P., Kuennzi, E. W., and Stamm, A. J.). *Springer-Verlag,* Berlin (703 pp).

SULAIMAN, O. (1993). The development of soft rot decay in bamboo cell walls. PhD Thesis, *Department of Biology, Imperial College of Science, Technology and Medicine*, London (305 pp).

TAYLOR, F. W. (1991). Variations in CCA Penetration and Retention in Loblolly and Shortleaf Pines. *Forest Products Journal,* **41** (11/12): 25-8

THOMAS, R. J. (1969). The ultrastructure of southern pine bordered pit membranes as revealed by specialised drying techniques. *Wood and Fiber,* **1** (2): 110-123.

THOMAS, R. J. and KRINGSTAD, K. P. (1971). The role of hydrogen bonding in pit aspiration. *Holzforschung,* **25** (5): 143-9

THOMAS, R. J. and NICHOLAS, D. D. (1966). Pit membrane structure in Loblolly pine as influenced by solvent exchange drying. *Forest Products Journal,* **16** (3): 53-56.

THOMAS, R. J. and NICHOLAS, D. D. (1968). The ultrastructure of the pinoid pit in southern yellow pine. *Tappi,* **LI**: 84-88.

THOMPSON, D. A. (1992). Growth of Sitka spruce and timber quality. Super Sitka for the 90`s. *Forestry Commission,* Bulletin **103**: 54-60.

TIEMANN, H. D. (1944). Wood Technology; Constitution, Properties & Uses. *Pitman Publishing Co.* New York (328 pp).

T. R. A. D. A. , (1986). Timber preservation. 3rd edition. Timber Research and Development Association, High Wycombe (51 pp).

TSOUMIS, G. (1964). Microscopic measurement of the amount of cell wall substance in wood and its relationship to specific gravity. *Tappi*, **47** (11): 675-677.

TSOUMIS, G. T. (1991). Science and technology of wood: structure, properties, utilisation. *Van Nostrand Reinhold*, New York (494 pp).

UPRICHARD, J. M. (1993). Primary wood processing: principles and practice. *Chapman & Hall Ltd*, London (595 pp).

WALKER, J. C. F. (1984). The effect of maturation on wood specific gravity of *Pinus radiata.* MSc Thesis, *University of California*, Berkeley (88 pp).

WALKER, J. C. F. (1993). Primary wood processing, principles and practice. *Chapman and Hall Ltd.* , London.

WARDROP, A. B. (1964). The structure and formation of the cell wall in xylem. The formation of wood in forest trees (ed. by M. H. Zimmermann). *Academic Press,* New York.

WARDROP, A. B. and DAVIES, G. W. (1961) Morphological Factors Relating to the Penetrations of Liquids into Wood. *Holzforschung,* **15** (5): 129-141

WEATHERWAX, R. C. and TARKOW, H. (1968). Cell wall density of dry wood. *Forest Products Journal,* **18** (2): 83-85

WHEELER, R. (1964). Equipment suitable for measuring angle of grain and for obtaining small timber samples from living trees. *Commonwealth Forestry Review,* **43** (4): 314-319.

WILCOX, W. W. (1973). Degradation in relation to wood structure. Degradation and protection of wood, wood deterioration and its prevention by preservative treatments (ed. by D. D. Nicholas), Vol. 1 (pp 107-148). *Syracuse University Press.* New York

WILKINSON, J. G. (1979). Industrial Timber Preservation. *Associated Business Press.* London (532 pp).

WILLEITNER, H. and MURPHY, R. J. (1987). Washboard effect: a surface deformation of Spruce resulting from vacuum-pressure impregnation with water-borne preservatives. *International Research Group on Wood Preservation.* Document No: IRG/WP/3450.

WILSON, K. and WHITE, D. J. B. (1986). The anatomy of wood: its diversity and variability. *Stobart & Son Ltd.* London (309 pp).

WODZICKI, T. J. and BRAWN, C. L. (1973). Cellular differentiation of the cambium in the Pinaceae. *Botanic Gazette,* **134**: 139-146.

WORRELL, R. (1987). Predicting the productivity of Sitka spruce on upland sites in northern Britain. *Forestry Commission Bulletin,* **72** (12 pp).

ZOBEL, B. J. and van BUJITENEN, J. P. (1980). Wood variation: its causes and control. *Springer-Verlag,* Berlin (363 pp).

Rhondda: Alaska (AL)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	10.40	2.5	5.55	433.79	46.31	22.39
tree 2	10.93	2.6	5.36	368.13	45.41	23.06
tree 3	11.56	2.4	5.55	373.20	44.95	21.98
tree 4	12.33	2.7	5.15	382.45	49.67	30.30
tree 5	12.33	2.6	5.47	414.02	68.04	22.02
mean	11.51	2.5	5.42	394.32	50.88	23.95
3m height	9.46	2.5	5.54	394.76	43.75	19.02
2m height	11.44	2.4	5.48	386.73	56.34	20.53
1m height	13.64	2.8	5.23	401.49	52.54	32.30
mean	11.51	2.5	5.42	394.32	50.88	23.95

Dalby: Alaska (AL)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	10.16	5.1	2.78	423.15	52.81	31.12
tree 2	10.20	4.8	2.91	481.69	68.25	18.58
tree 3	10.96	4.3	3.26	423.06	49.78	11.88
tree 4	11.20	5.3	2.66	466.70	65.27	9.63
tree 5	13.46	3.6	4.32	452.26	56.63	15.74
mean	11.20	4.6	3.19	449.37	58.55	17.39
3m height	9.96	4.1	3.72	444.50	49.74	20.12
2m height	11.30	4.8	2.97	441.16	60.29	9.99
1m height	12.34	5.0	2.86	462.48	65.61	22.06
mean	11.20	4.6	3.19	449.37	58.55	17.39

Rhondda: British Colombia (BC)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	11.43	2.7	5.29	411.91	36.73	24.93
tree 2	12.13	2.5	5.50	353.57	42.32	24.84
tree 3	11.83	3.4	4.27	390.30	47.49	18.30
tree 4	12.06	2.6	5.14	372.46	53.62	24.85
tree 5	14.76	2.7	5.18	385.98	68.08	16.41
mean	12.44	2.7	5.08	382.85	49.65	21.87
3m height	10.64	2.6	5.22	378.52	49.07	22.97
2m height	12.38	2.7	5.12	380.56	53.41	19.28
1m height	14.32	3.1	4.89	389.49	46.46	23.35
mean	12.44	2.7	5.08	382.85	49.65	21.87

Dalby: British Colombia (BC)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	12.26	3.7	3.77	354.75	44.02	15.31
tree 2	12.56	5.3	2.71	455.70	68.22	13.81
tree 3	13.50	4.8	3.12	429.00	69.39	10.08
tree 4	14.83	4.2	3.45	370.27	64.71	23.24
tree 5	16.70	2.8	4.92	347.38	68.62	17.08
mean	13.97	4.1	3.59	391.42	62.99	15.90
3m height	12.84	3.5	4.11	382.00	67.81	19.37
2m height	14.00	4.4	3.38	393.40	57.82	13.01
1m height	15.08	4.6	3.29	398.90	63.36	15.33
mean	13.97	4.1	3.59	391.42	62.99	15.90

Rhondda: Queen Charlotte Islands (QCI)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	11.63	3.1	4.75	402.48	59.22	38.14
tree 2	11.33	3.0	4.62	503.05	62.25	23.70
tree 3	13.96	3.7	3.91	413.35	50.70	16.08
tree 4	12.60	2.7	5.29	388.82	48.37	28.02
tree 5	14.48	2.3	6.28	405.63	73.50	21.15
mean	12.80	2.9	4.97	422.67	58.81	25.42
3m height	10.94	2.7	5.37	416.20	55.80	18.08
2m height	12.72	3.0	4.89	425.50	60.26	30.95
1m height	14.75	3.3	4.65	426.40	60.36	27.22
mean	12.80	2.9	4.97	422.67	58.81	25.42

Dalby: Queen Charlotte Islands (QCI)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	14.56	4.8	3.10	470.40	82.44	23.31
tree 2	14.73	4.3	3.35	385.20	57.34	13.85
tree 3	16.33	5.0	2.85	410.34	78.06	25.98
tree 4	16.80	3.3	4.41	381.80	51.32	11.43
tree 5	17.66	3.0	4.72	355.00	75.87	44.52
mean	16.02	4.0	3.69	400.56	69.01	23.82
3m height	14.68	3.6	4.16	398.10	68.11	30.15
2m height	15.98	4.0	3.82	394.70	70.27	20.31
1m height	17.40	4.8	3.08	408.90	68.63	20.99
mean	16.02	4.0	3.69	400.56	69.01	23.82

Rhondda: North Washington (NW)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	11.83	4.2	3.46	500.60	59.97	27.64
tree 2	11.60	3.7	3.73	486.29	59.85	28.80
tree 3	12.03	3.3	4.17	412.69	64.30	19.33
tree 4	12.10	3.5	4.15	446.30	64.43	22.36
tree 5	12.76	3.6	4.23	387.46	48.53	16.48
mean	12.06	3.6	3.95	446.67	59.42	22.92
3m height	10.40	2.9	4.85	429.60	52.39	10.74
2m height	12.08	3.7	3.78	454.40	66.72	25.98
1m height	13.72	4.4	3.21	456.00	59.14	32.04
mean	12.06	3.6	3.95	446.67	59.42	22.92

Dalby: North Washington (NW)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	12.76	4.2	3.43	376.49	58.01	14.16
tree 2	13.10	4.8	2.96	422.68	73.43	20.31
tree 3	13.53	3.8	3.64	447.26	78.07	18.22
tree 4	14.33	3.3	4.39	373.45	57.96	18.71
tree 5	14.10	4.2	3.38	488.75	74.78	10.98
mean	13.56	4.0	3.56	421.73	68.45	16.48
3m height	12.16	3.5	4.13	413.50	61.34	14.37
2m height	13.62	4.5	3.23	426.40	72.27	14.06
1m height	14.92	4.3	3.33	425.30	71.73	21.00
mean	13.56	4.0	3.56	421.73	68.45	16.48

Rhondda: South Washington (SW)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	11.26	4.2	3.31	479.38	67.91	16.68
tree 2	12.16	3.2	4.49	371.83	50.43	23.68
tree 3	13.10	4.1	3.49	429.67	65.51	28.49
tree 4	13.56	2.7	5.07	420.91	57.37	14.74
tree 5	14.33	3.5	4.21	449.31	52.84	15.94
mean	12.88	3.5	4.11	430.22	58.81	19.91
3m height	11.52	3.0	4.65	414.41	58.21	15.87
2m height	12.86	3.8	3.87	434.10	65.36	16.51
1m height	14.28	3.9	3.83	442.20	52.87	27.34
mean	12.88	3.5	4.11	430.22	58.81	19.91

Dalby: South Washington (SW)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	11.53	4.8	2.95	396.92	53.33	11.67
tree 2	12.76	5.3	2.64	454.62	72.47	17.29
tree 3	13.83	4.0	3.68	402.42	60.34	16.33
tree 4	14.23	4.6	3.09	446.11	60.06	7.89
tree 5	14.40	3.5	3.95	374.93	59.32	8.69
mean	13.35	4.4	3.26	415.00	61.10	12.37
3m height	12.32	4.2	3.49	398.05	61.94	12.85
2m height	13.62	4.4	3.28	415.31	63.58	11.24
1m height	14.12	4.8	3.02	431.64	57.79	13.03
mean	13.35	4.4	3.26	415.00	61.10	12.37

Rhondda: North Oregon (NO)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	13.00	2.6	5.39	448.80	43.03	24.73
tree 2	11.93	2.9	4.82	441.94	42.06	20.08
tree 3	12.80	2.1	6.38	371.64	33.76	11.08
tree 4	13.10	3.2	4.41	415.20	45.44	13.65
tree 5	13.70	3.1	4.76	415.60	51.80	21.11
mean	12.91	2.7	5.15	418.64	43.22	18.13
3m height	11.18	2.7	5.22	421.60	44.75	14.72
2m height	12.84	2.9	4.94	416.80	50.47	18.74
1m height	14.70	2.7	5.30	417.50	34.43	20.93
mean	12.91	2.7	5.15	418.64	43.22	18.13

Dalby: North Oregon (NO)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	9.46	4.4	3.27	456.72	41.84	30.01
tree 2	11.70	4.8	3.08	405.48	58.33	16.70
tree 3	12.46	5.6	2.54	396.52	51.71	15.48
tree 4	13.83	4.2	3.32	474.94	87.10	13.55
tree 5	15.96	3.5	4.35	417.76	54.06	11.15
mean	12.68	4.5	3.31	430.28	58.61	17.38
3m height	11.56	3.9	3.80	412.93	57.18	21.71
2m height	12.70	4.4	3.34	438.90	58.83	16.29
1m height	13.80	5.2	2.79	438.97	59.80	14.14
mean	12.68	4.5	3.31	430.28	58.61	17.38

Rhondda: South Oregon (SO)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	10.53	3.7	3.84	504.90	49.82	11.75
tree 2	12.30	4.0	3.57	470.92	48.53	13.44
tree 3	11.80	3.3	4.20	444.20	42.42	11.03
tree 4	13.20	2.6	5.33	427.70	52.75	18.04
tree 5	13.43	3.2	4.41	443.10	70.70	24.20
mean	12.25	3.3	4.27	458.16	52.84	15.69
3m height	10.98	2.9	4.83	440.51	51.30	9.46
2m height	12.02	3.5	4.06	464.60	55.38	14.38
1m height	13.76	3.7	3.92	469.41	51.85	23.24
mean	12.25	3.3	4.27	458.16	52.84	15.69

Dalby: South Oregon (SO)

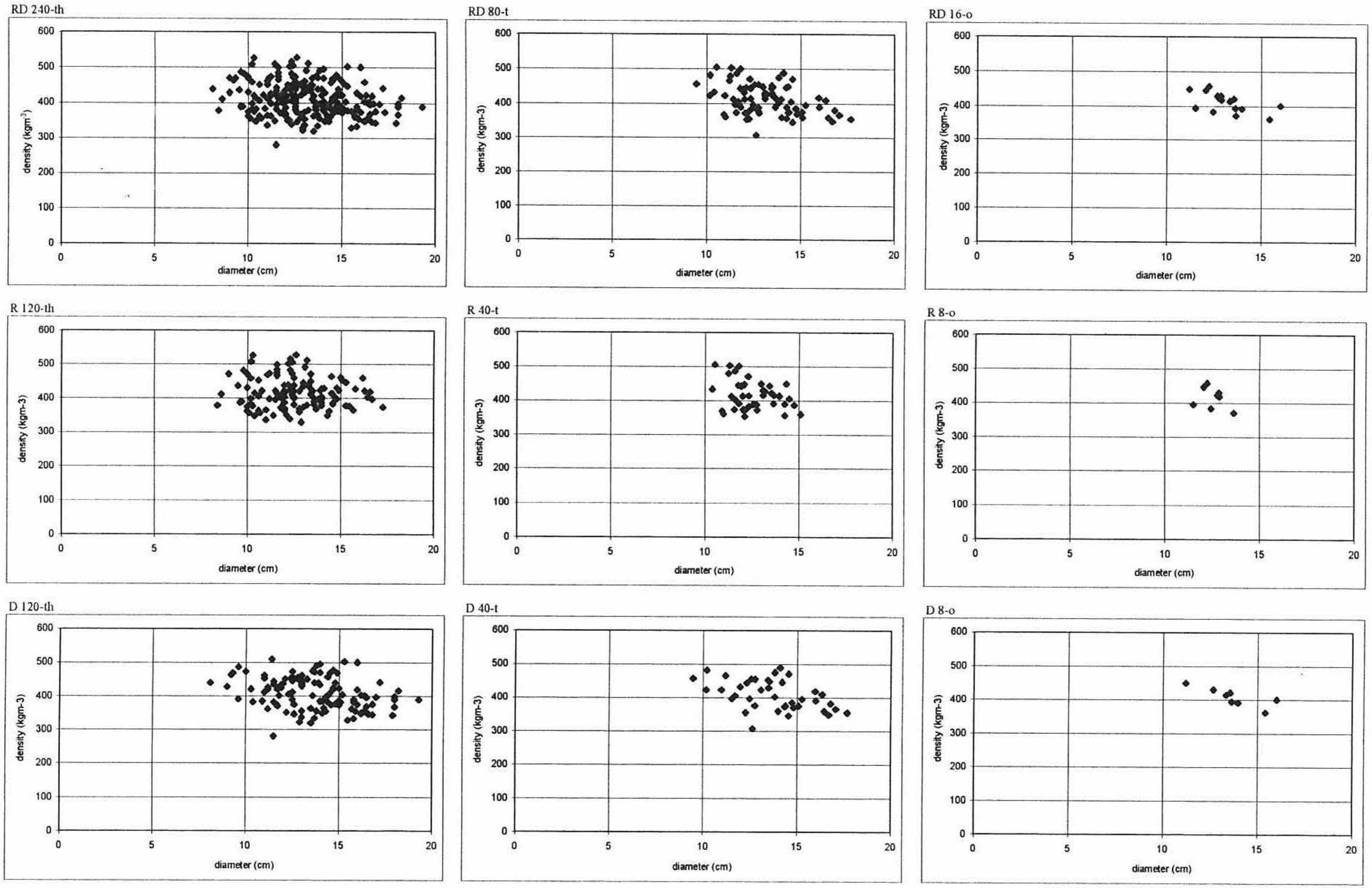
location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	12.33	5.3	2.74	444.24	80.04	9.27
tree 2	12.00	4.5	3.15	431.90	70.53	23.53
tree 3	12.63	3.5	4.18	307.43	65.18	15.14
tree 4	15.26	3.3	4.32	395.31	69.43	9.15
tree 5	16.00	4.1	3.56	390.73	69.95	11.92
mean	13.64	4.1	3.59	393.92	71.03	13.80
3m height	12.54	3.9	3.82	377.50	69.95	17.50
2m height	13.80	4.2	3.53	404.20	72.13	13.45
1m height	14.60	4.4	3.42	400.10	71.01	10.46
mean	13.64	4.1	3.59	393.92	71.03	13.80

Rhondda: California (CA)

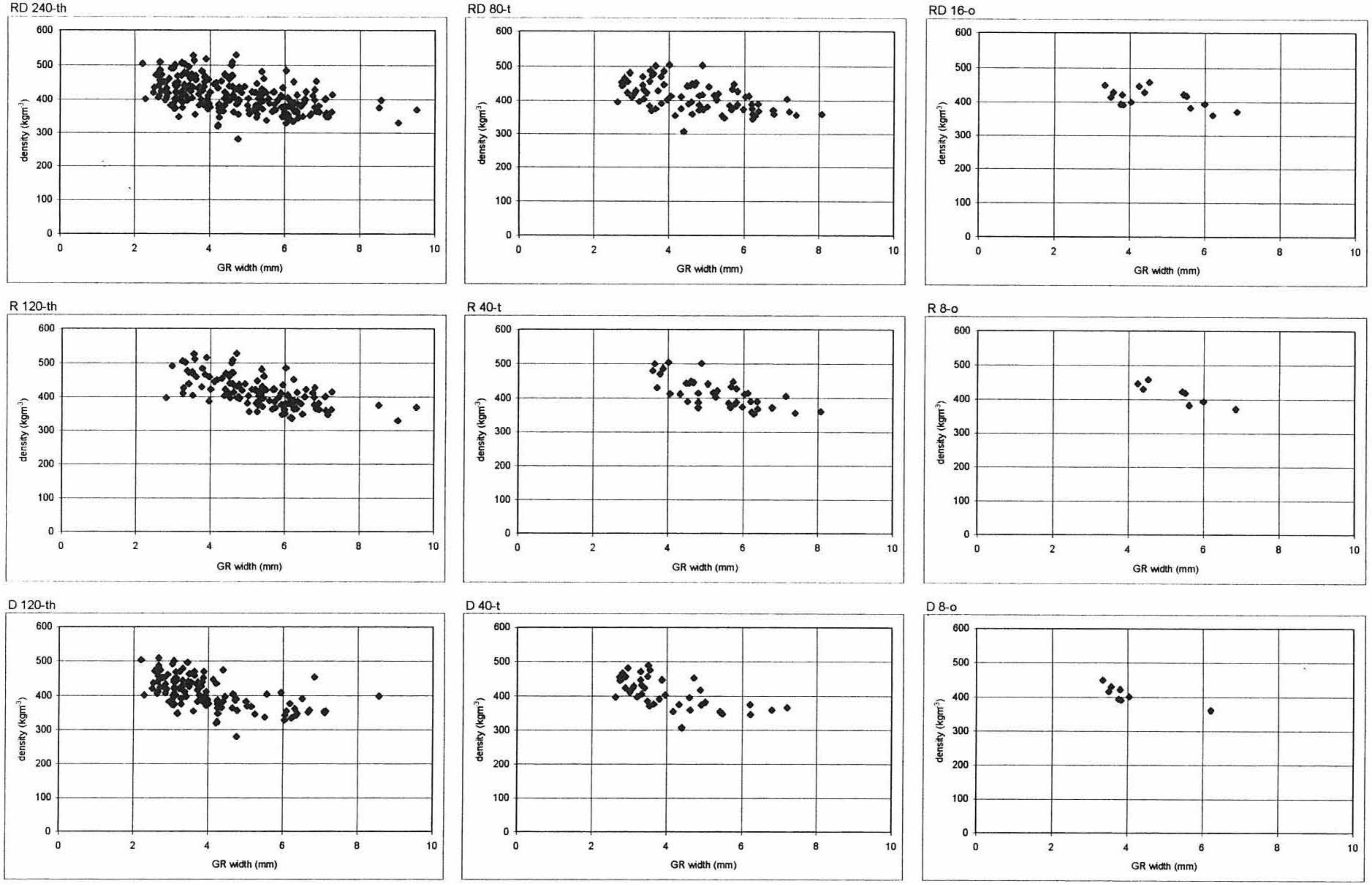
location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	11.00	2.2	6.66	360.40	58.96	18.28
tree 2	13.66	2.4	5.90	390.70	40.42	14.71
tree 3	14.26	2.1	6.66	356.20	59.29	23.18
tree 4	14.26	2.6	5.69	389.62	57.74	11.65
tree 5	15.10	2.3	5.96	359.30	48.38	20.32
mean	13.66	2.3	6.17	371.24	52.96	17.63
3m height	11.94	2.3	6.31	357.73	59.62	19.00
2m height	13.60	2.3	6.17	362.13	51.37	13.47
1m height	15.44	2.5	6.04	393.87	47.89	20.41
mean	13.66	2.5	6.18	371.24	52.96	17.63

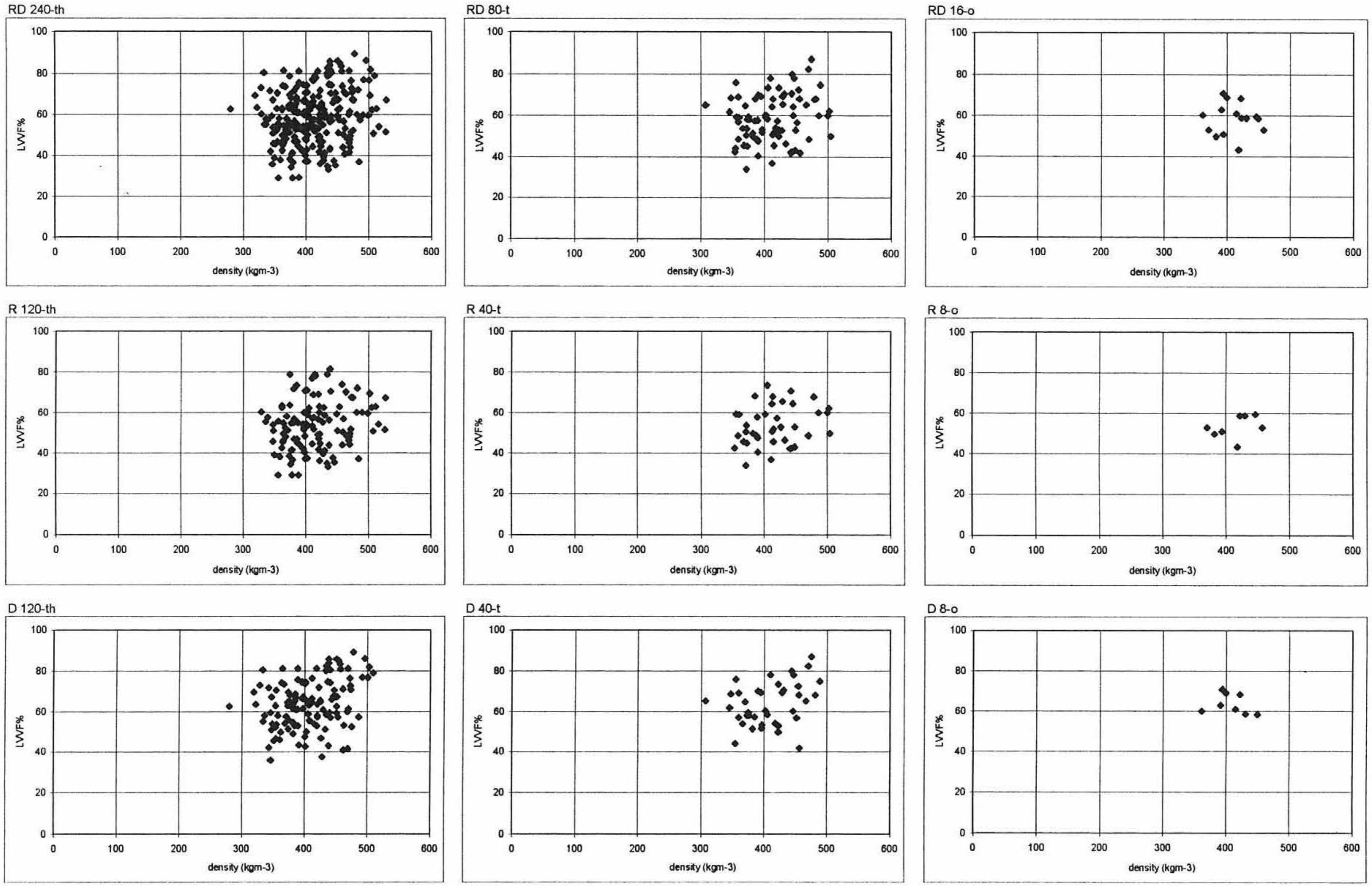
Dalby: California (CA)

location	dia (cm)	ring (no)	GR (mm)	density (kg/m^3)	LVVF (%)	RVVF (%)
tree 1	14.00	3.4	4.21	359.59	69.13	13.99
tree 2	14.56	2.5	5.87	345.37	61.74	16.82
tree 3	15.06	2.7	5.30	375.65	59.29	16.78
tree 4	16.47	2.2	6.36	359.62	57.00	19.11
tree 5	17.06	2.3	6.27	366.50	53.79	19.33
mean	15.43	2.6	5.60	361.35	60.19	17.21
3m height	14.72	2.5	5.69	346.60	59.05	16.39
2m height	15.32	2.8	5.43	358.45	59.45	19.46
1m height	16.26	2.6	5.69	378.98	62.07	15.76
mean	15.43	2.6	5.60	361.35	60.19	17.21

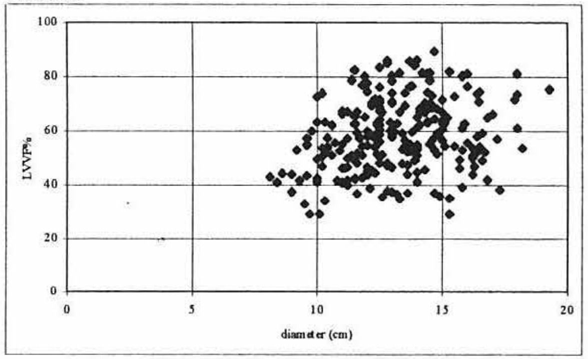


Appendix 2 - Relationships between the variables at height, tree and seed origin level

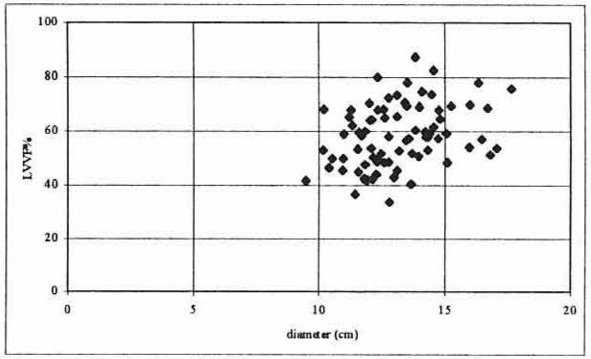

RD 240-th
RD 80-t
RD 16-o
R 120-th
R 40-t
R 8-o
D 120-th
D 40-t
D 8-o
density (kgm⁻³)
GR width (mm)
0
100
200
300
400
500
600
0
2
4
6
8
10


RD 240-th
RD 80-t
RD 16-o
R 120-th
R 40-t
R 8-o
D 120-th
D 40-t
D 8-o
LWF%
density (kgm-3)
0
20
40
60
80
100
100
200
300
400
500
600

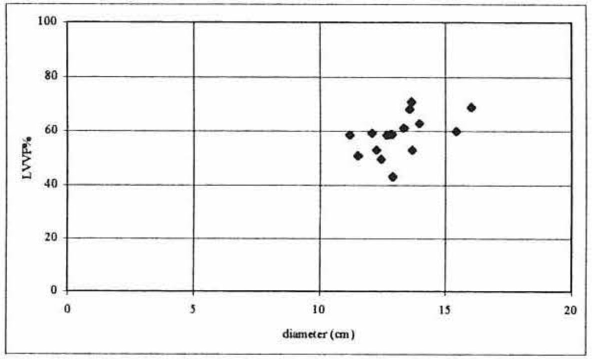
RD 240-th



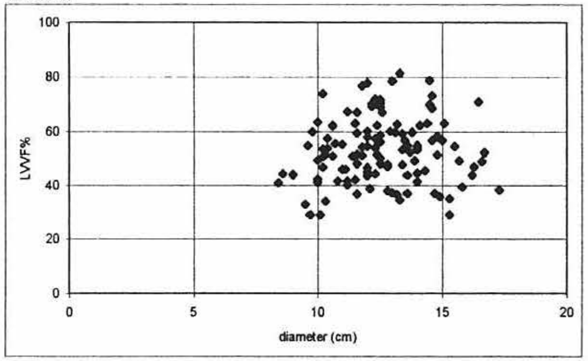
RD 80-t



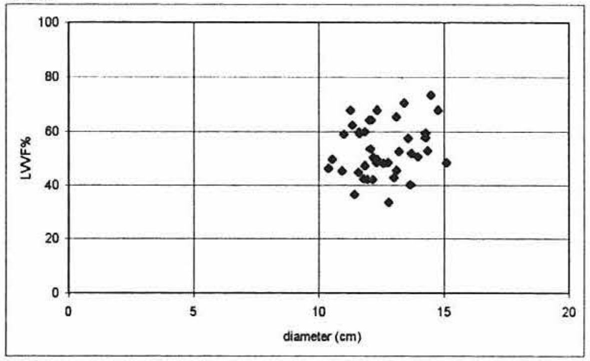
RD 16-o



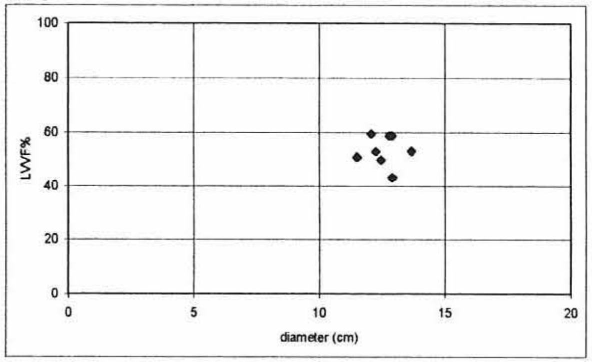
R 120-th



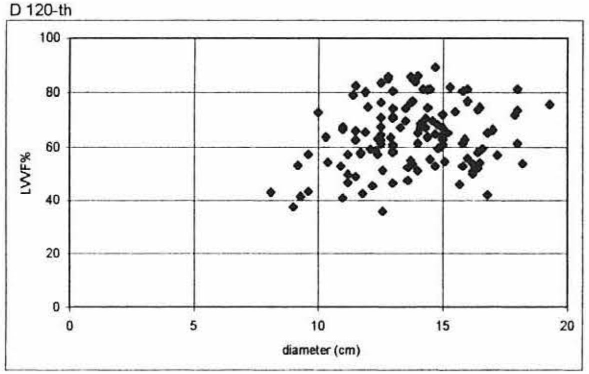
R 40-t



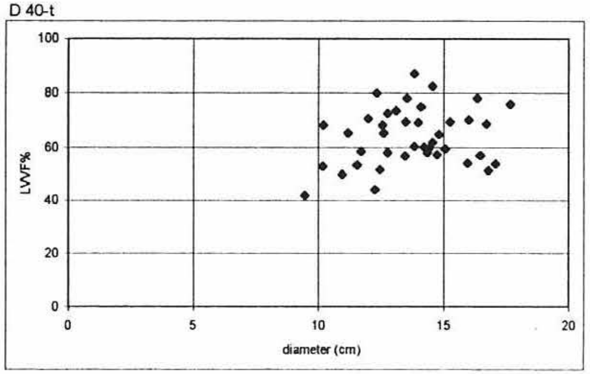
R 8-o



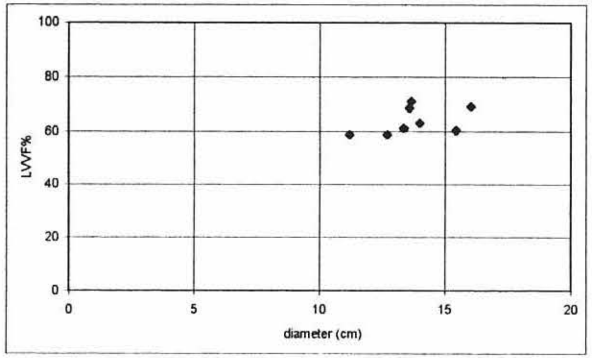
D 120-th

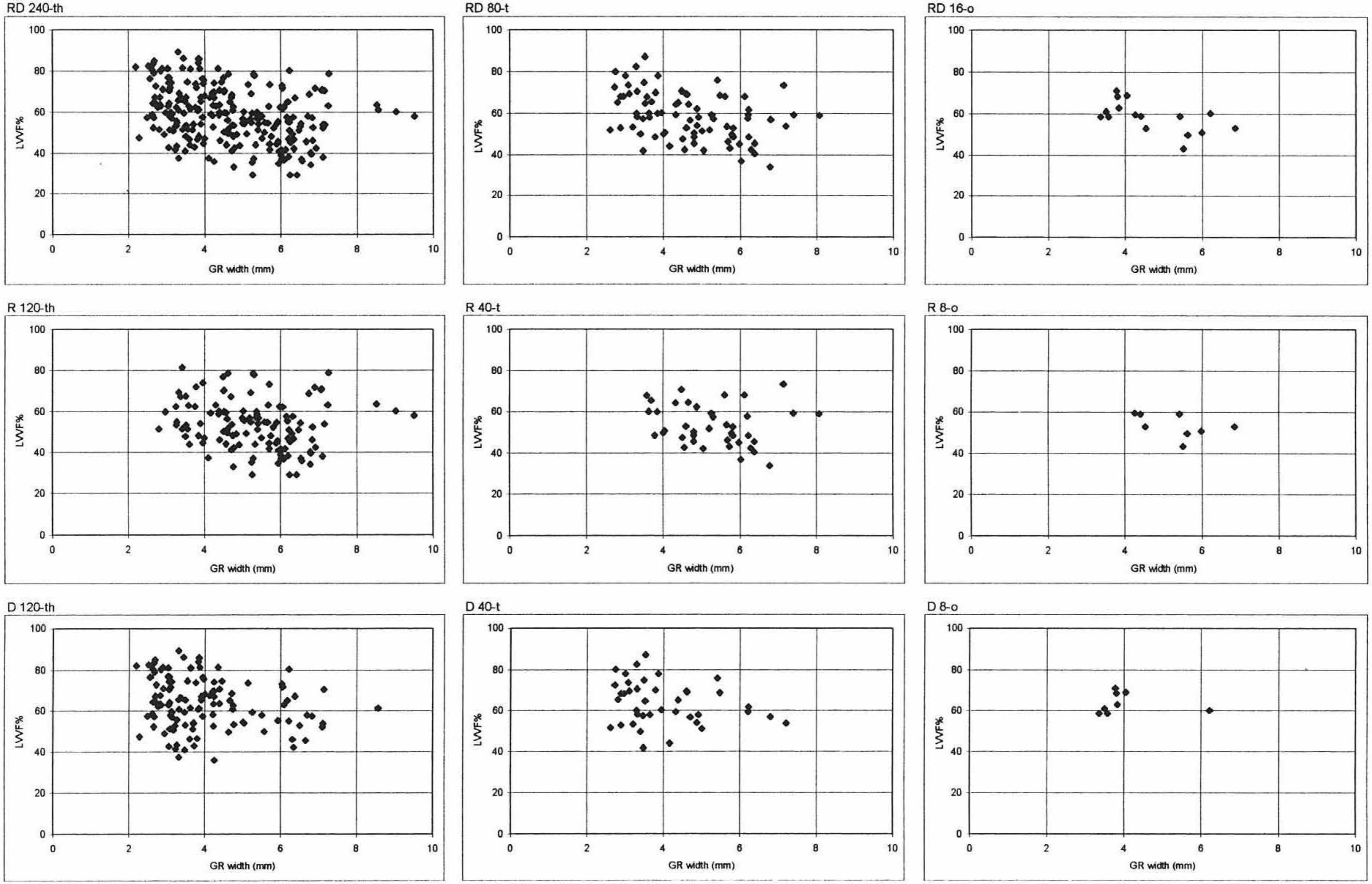


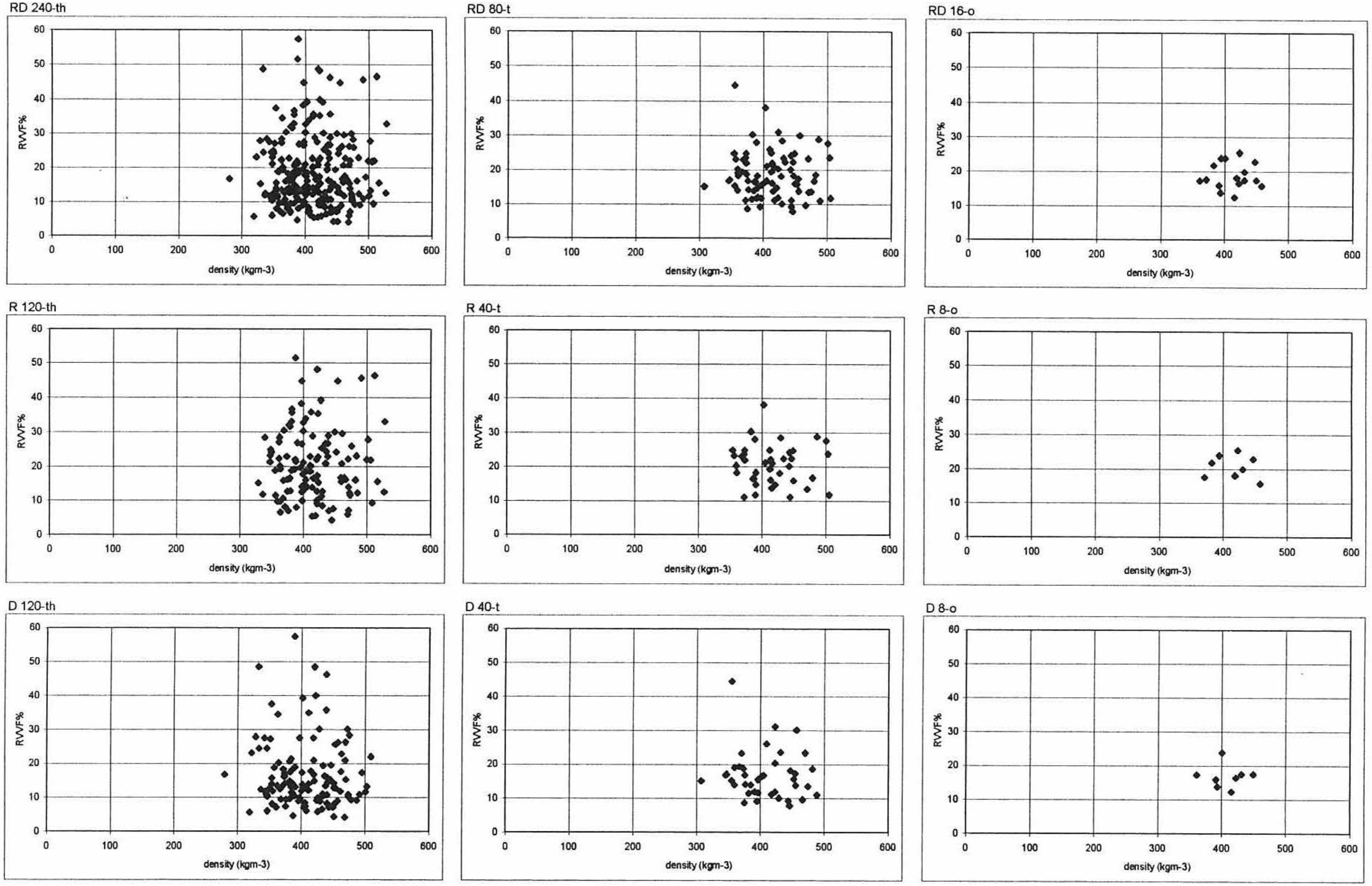
D 40-t

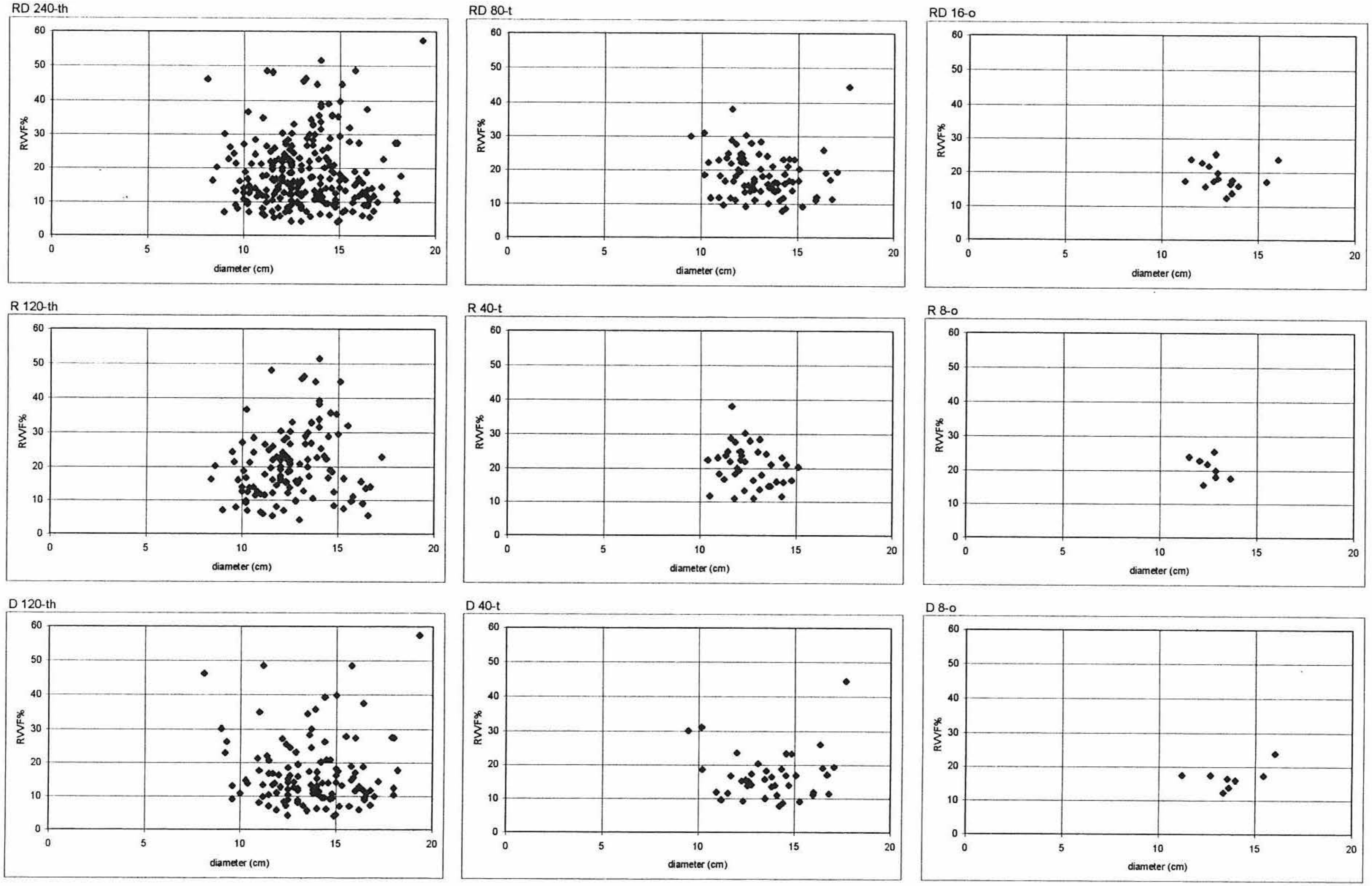


D 8-o

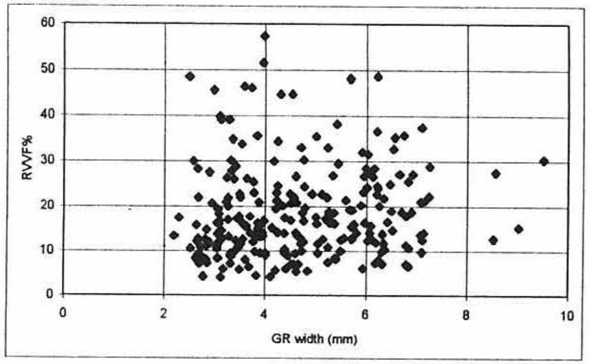



RD 240-th
RD 80-t
RD 16-o
R 120-th
R 40-t
R 8-o
D 120-th
D 40-t
D 8-o
LWF%
GR width (mm)

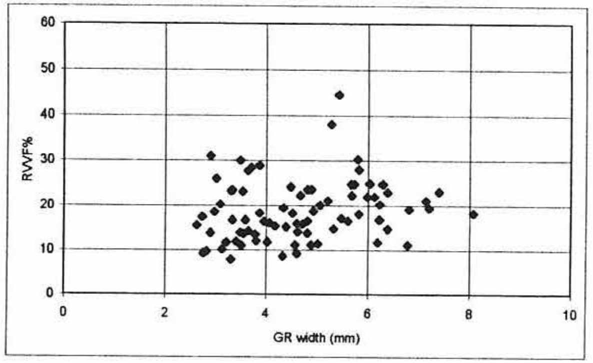

RD 240-th
RD 80-t
RD 16-o
R 120-th
R 40-t
R 8-o
D 120-th
D 40-t
D 8-o
RVVF%
density (kgm-3)
0
10
20
30
40
50
60
100
200
300
400
500
600


RD 240-th
RD 80-t
RD 16-o
R 120-th
R 40-t
R 8-o
D 120-th
D 40-t
D 8-o
RVVF%
diameter (cm)

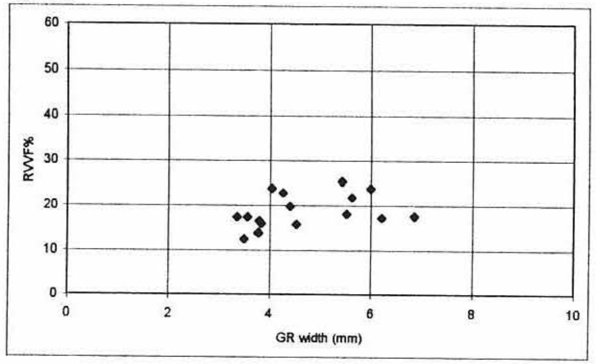
RD 240-th



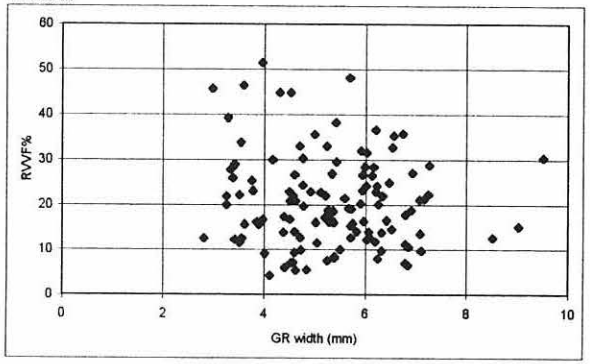
RD 80-t



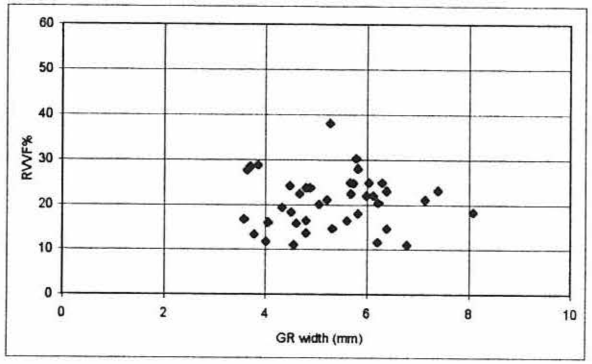
RD 16-o



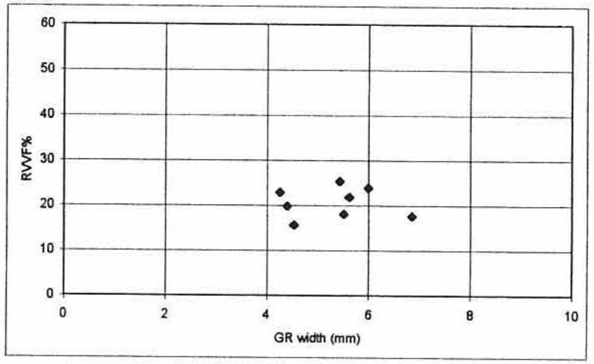
R 120-th



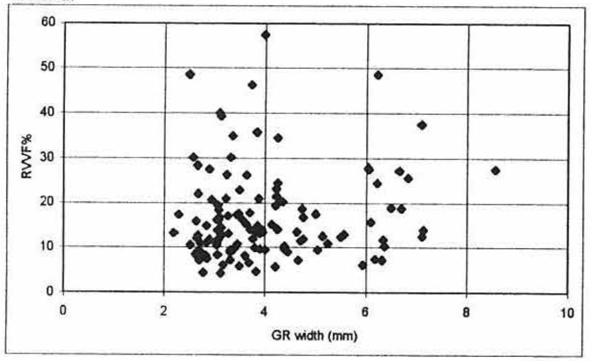
R 40-t



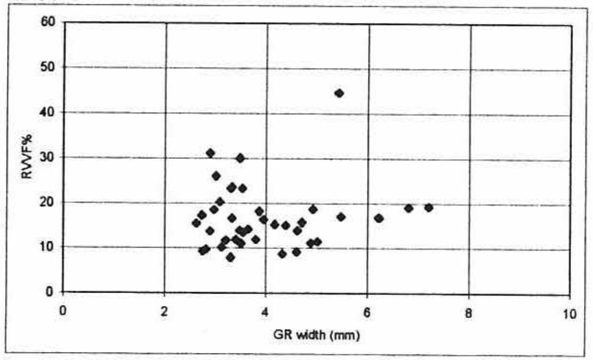
R 8-o



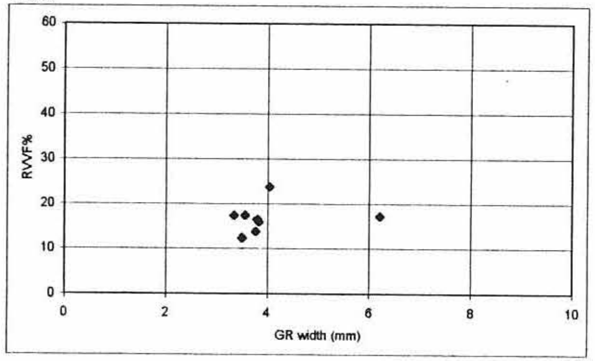
D 120-th

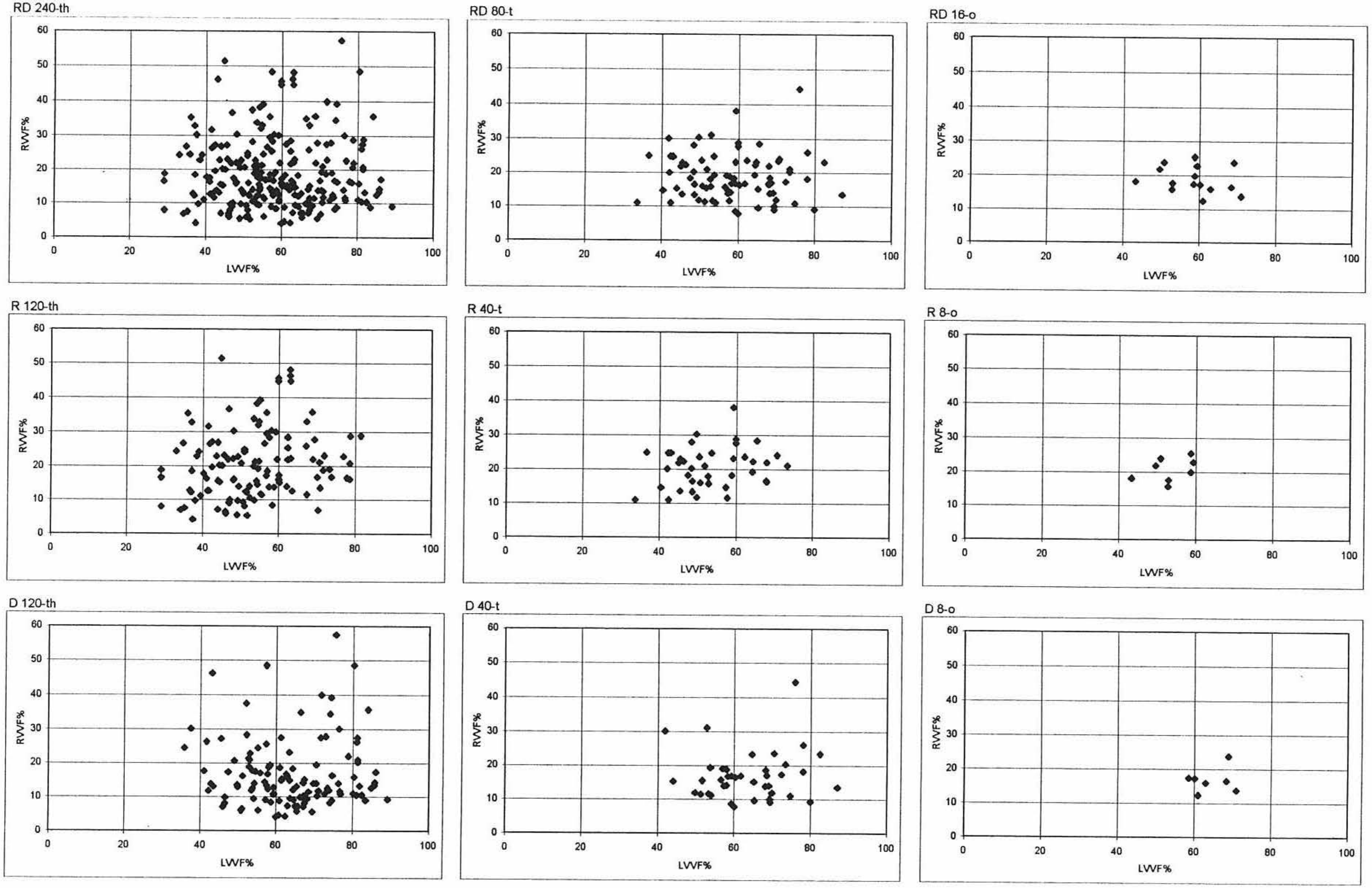


D 40-t

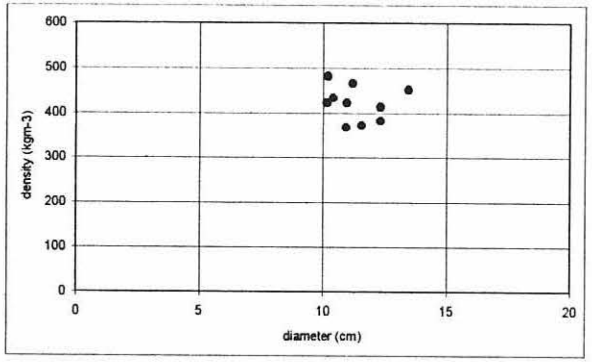


D 8-o

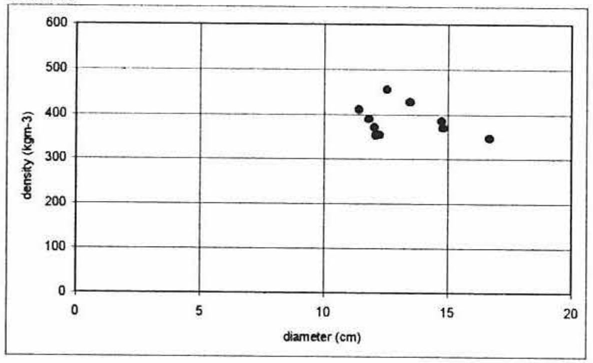



RD 240-th
RD 80-t
RD 16-o
R 120-th
R 40-t
R 8-o
D 120-th
D 40-t
D 8-o
RVVF%
LVVF%
0
10
20
30
40
50
60
80
100

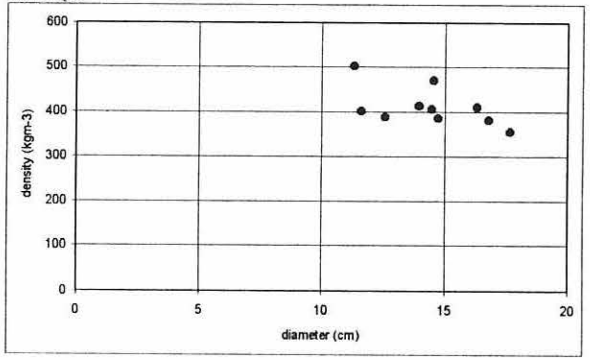
10RD-AL



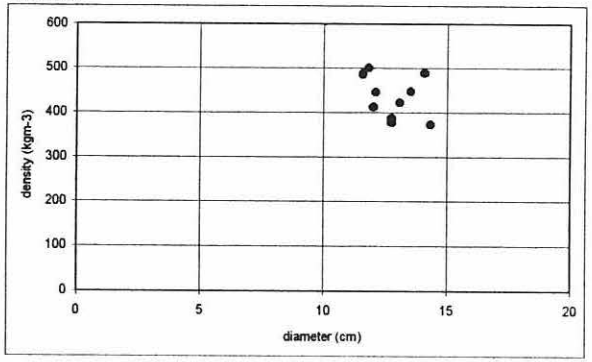
10RD-BC



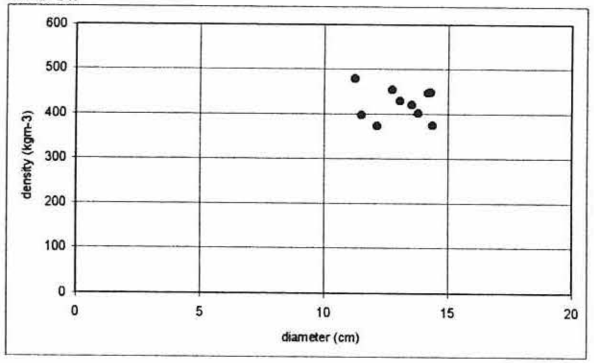
10RD-QCI



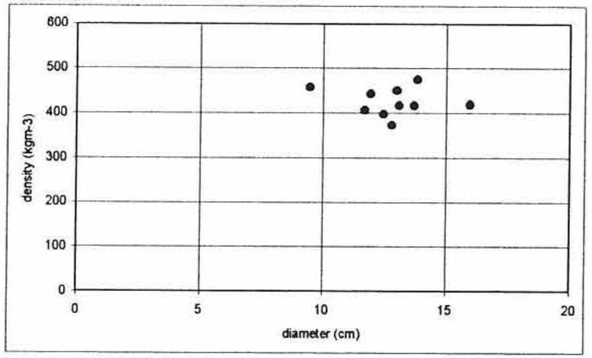
10RD-NW



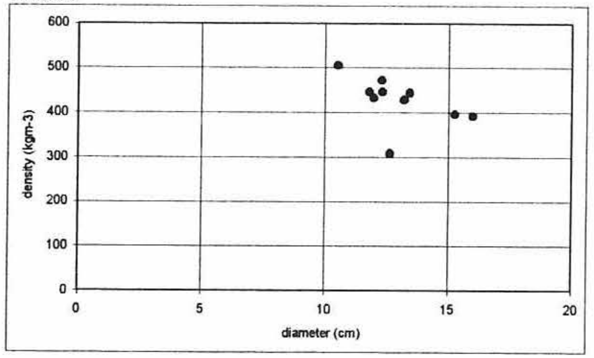
10RD-SW



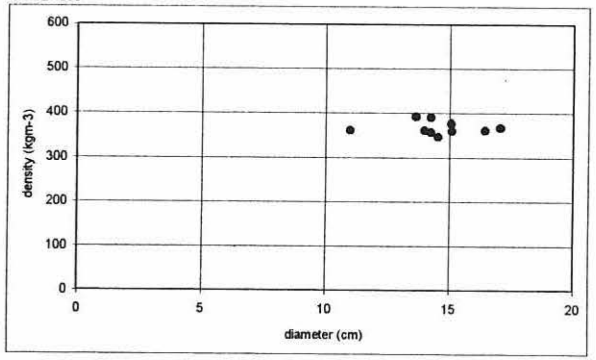
10RD-NO



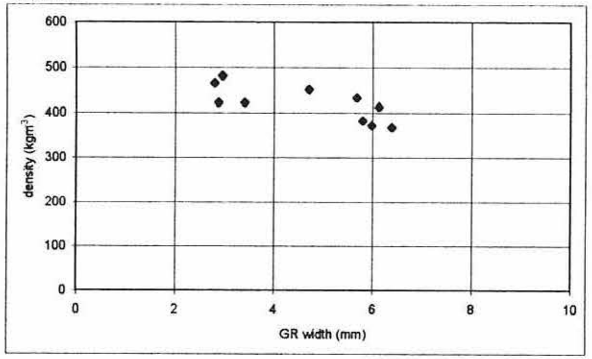
10RD-SO



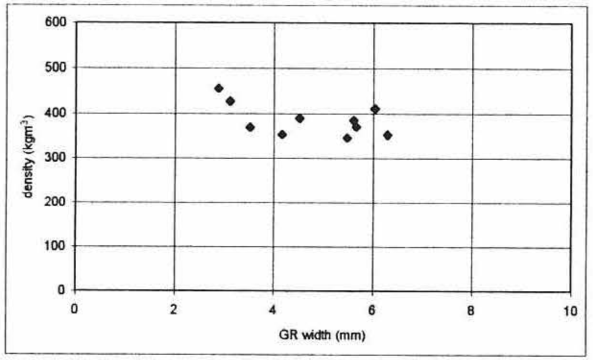
10RD-CA



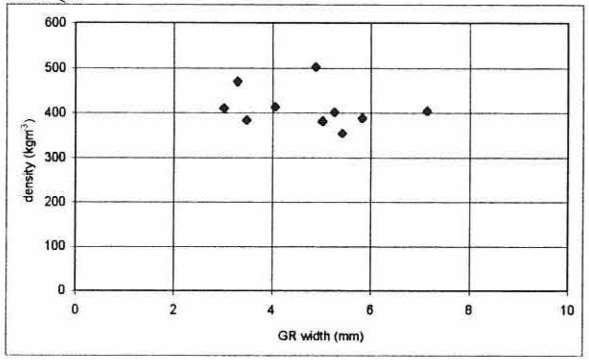
10RD-AL



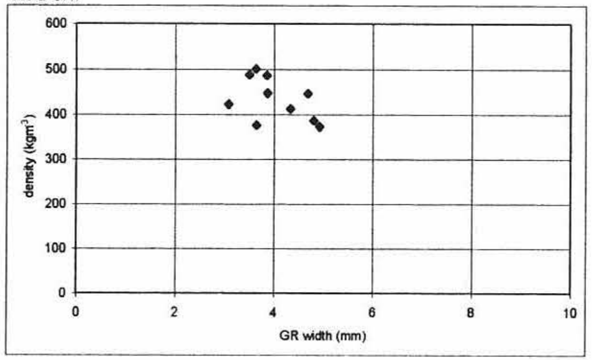
10RD-BC



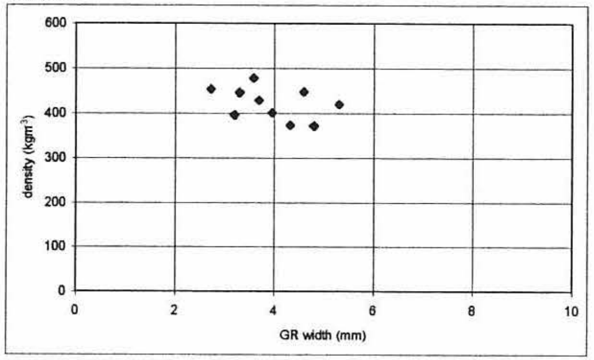
10RD-QCI



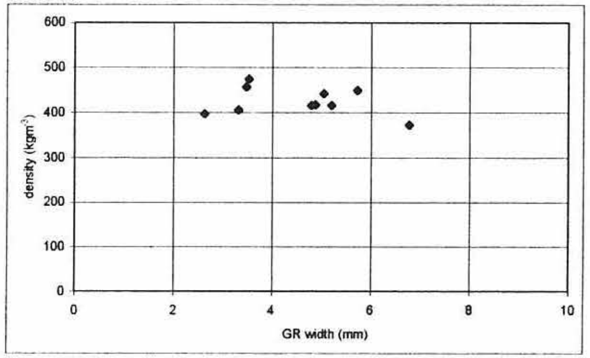
10RD-NW



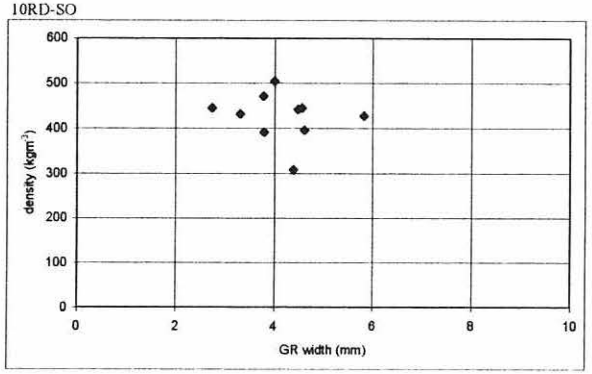
10RD-SW



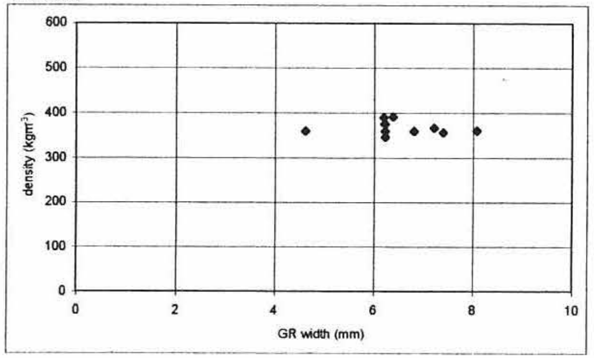
10RD-NO



10RD-SO

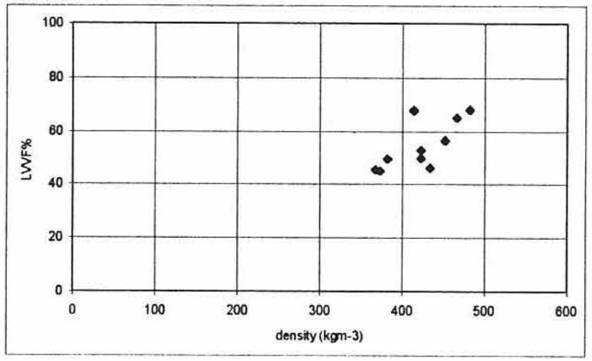


10RD-CA

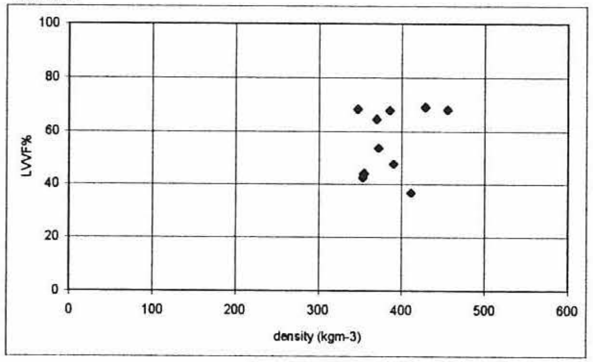


Appendix 3 - Relationships between the variables in trees of each seed origin

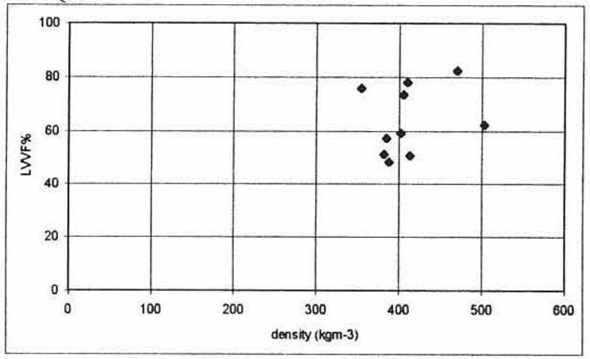
10RD-AL



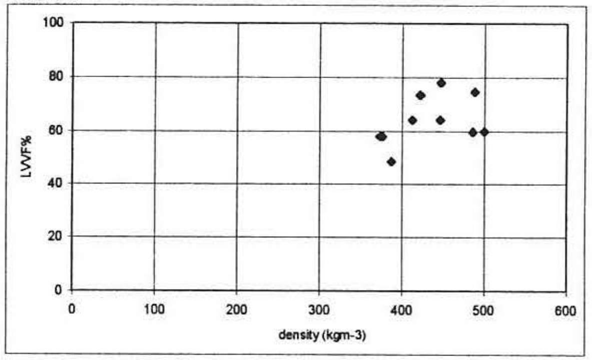
10RD-BC



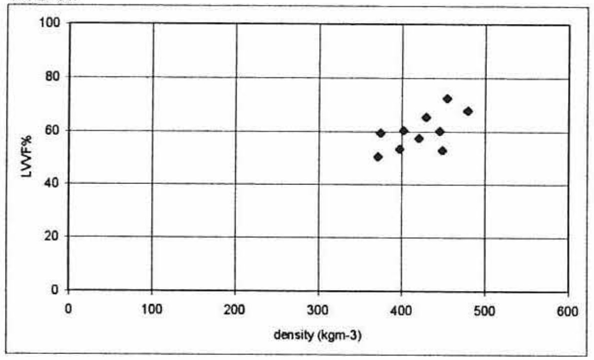
10RD-QCI



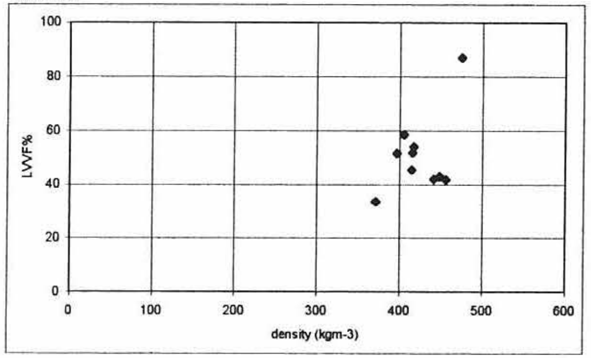
10RD-NW



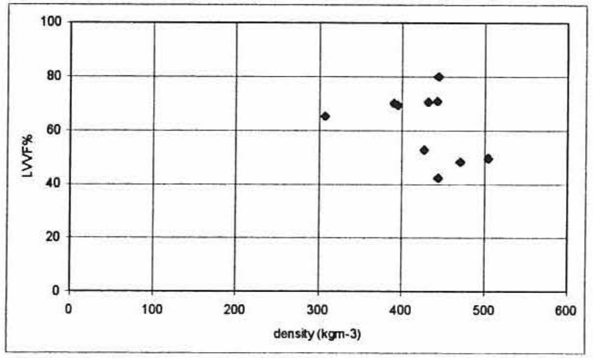
10RD-SW



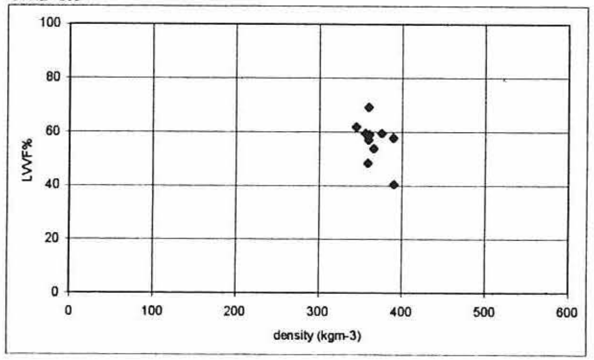
10RD-NO



10RD-SO

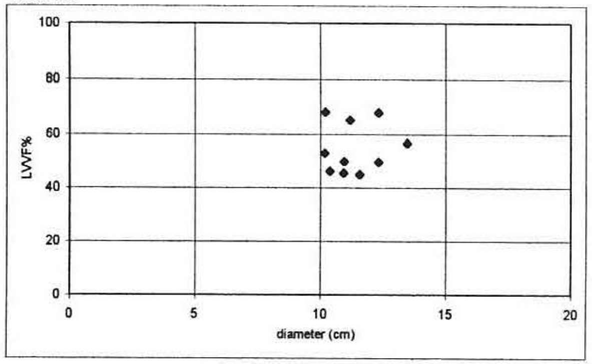


10RD-CA

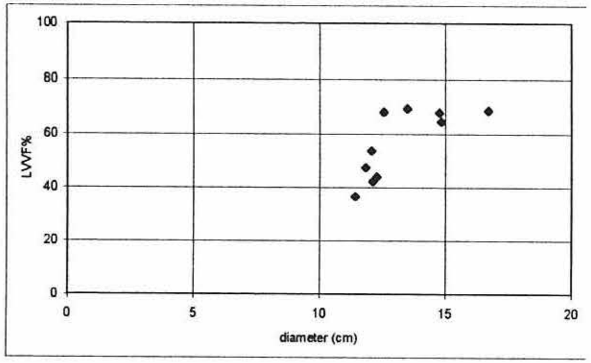


Appendix 3 - Relationships between the variables in trees of each seed origin

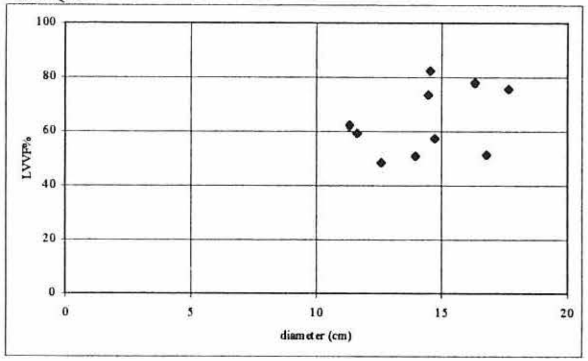
10RD-AL



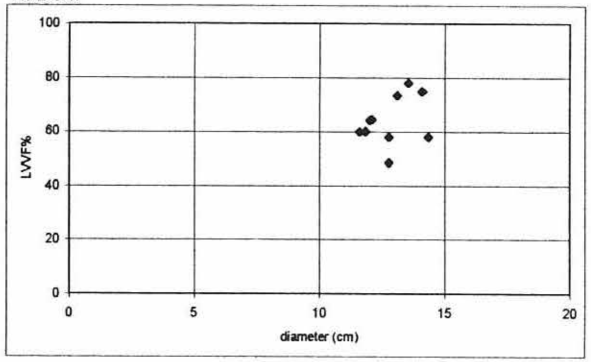
10RD-BC



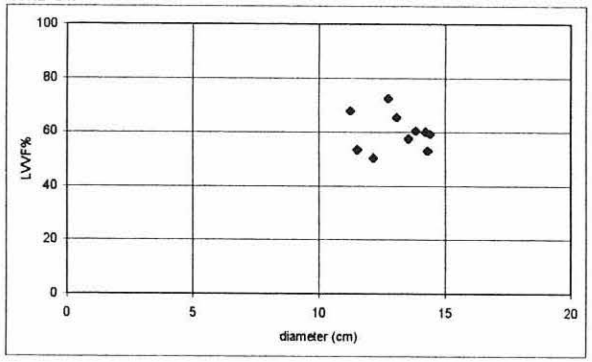
10RD-QCI



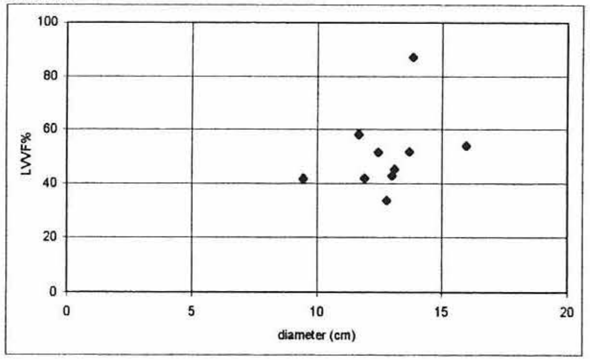
10RD-NW



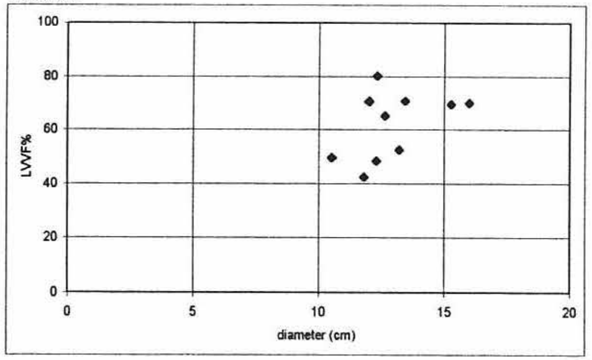
10RD-SW



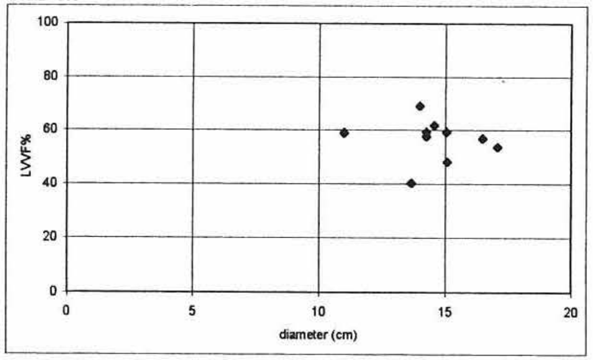
10RD-NO



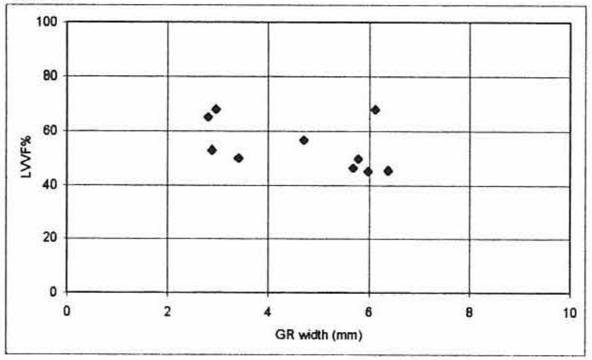
10RD-SO



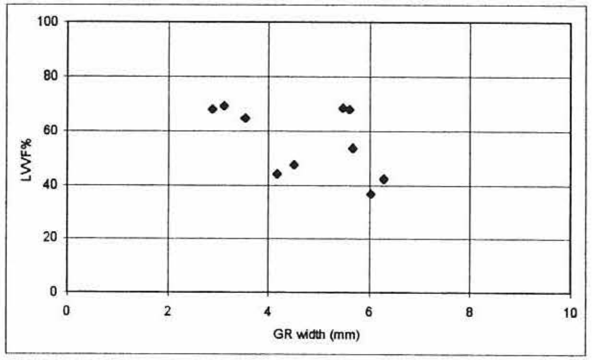
10RD-CA



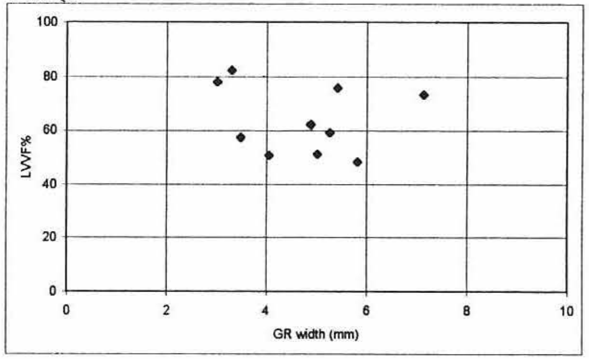
10RD-AL



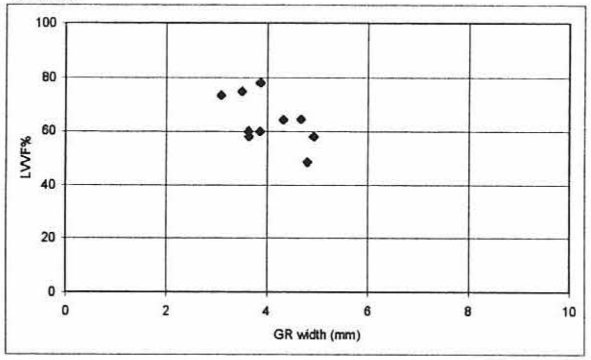
10RD-BC



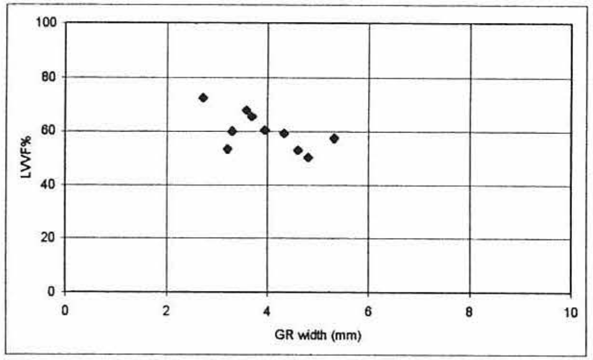
10RD-QCI



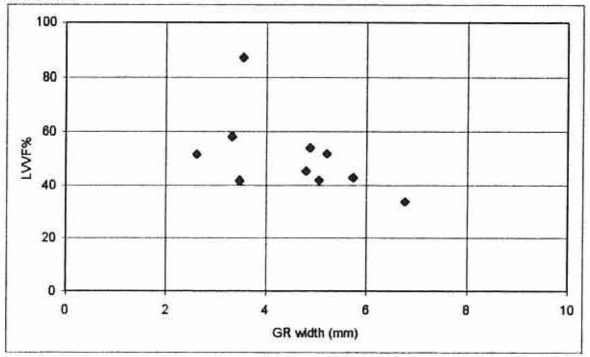
10RD-NW



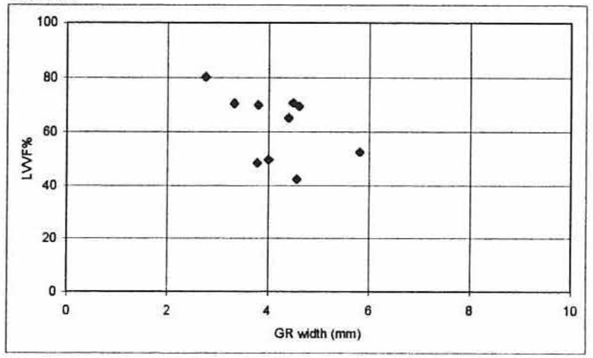
10RD-SW



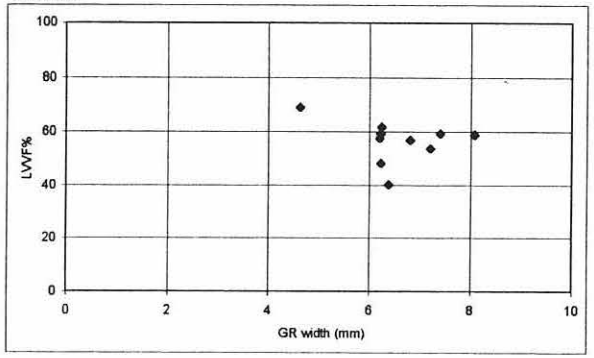
10RD-NO



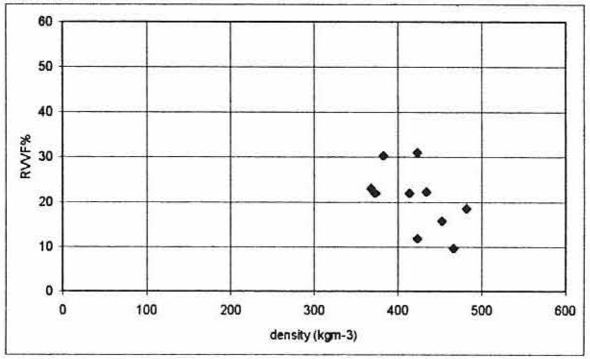
10RD-SO



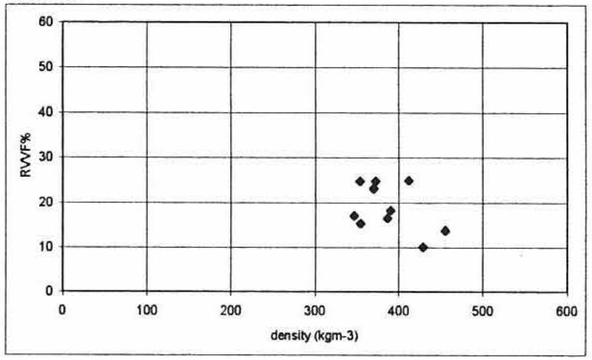
10RD-CA



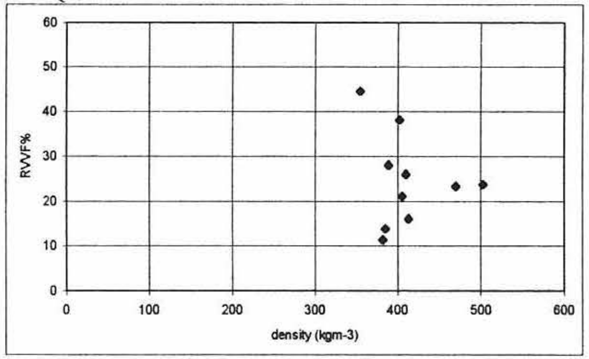
10RD-AL



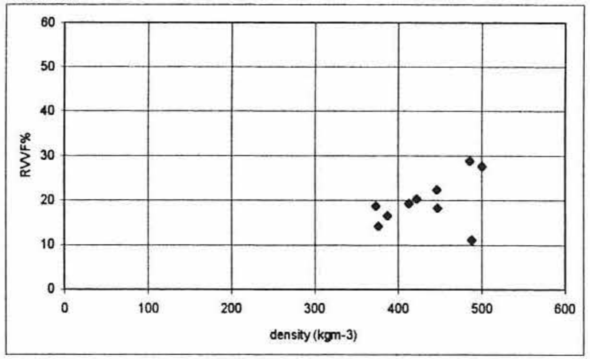
10RD-BC



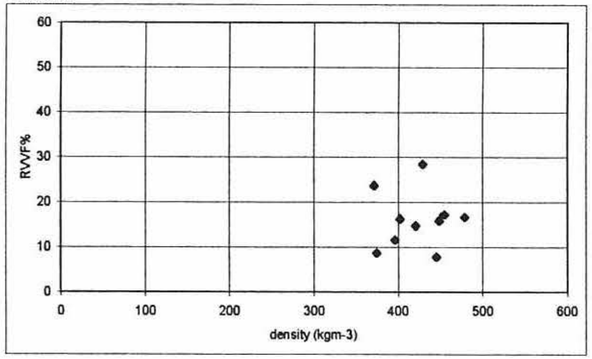
10RD-QCI



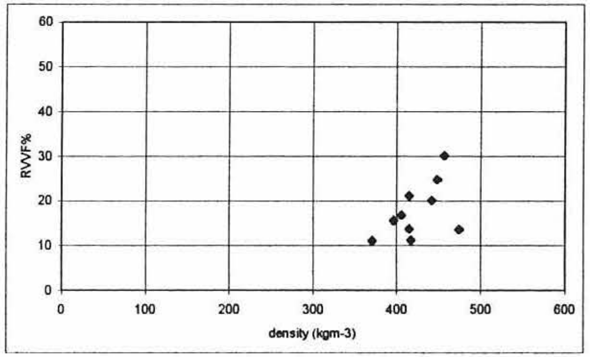
10RD-NW



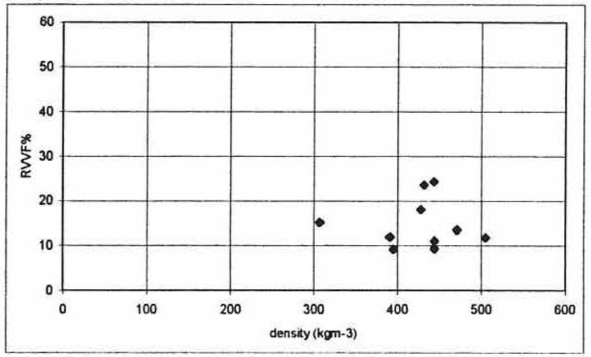
10RD-SW



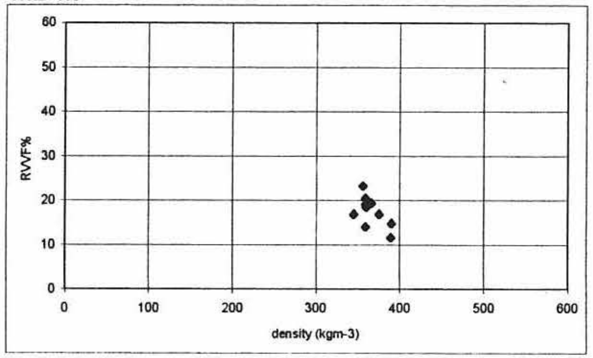
10RD-NO



10RD-SO

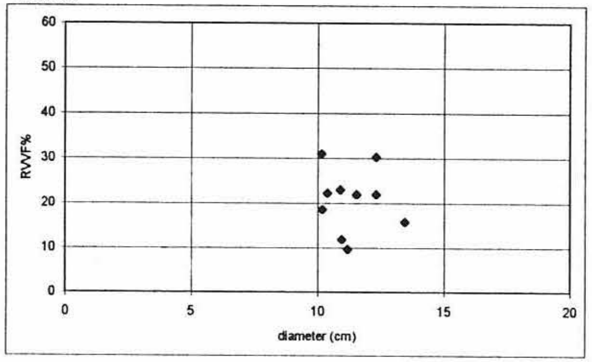


10RD-CA

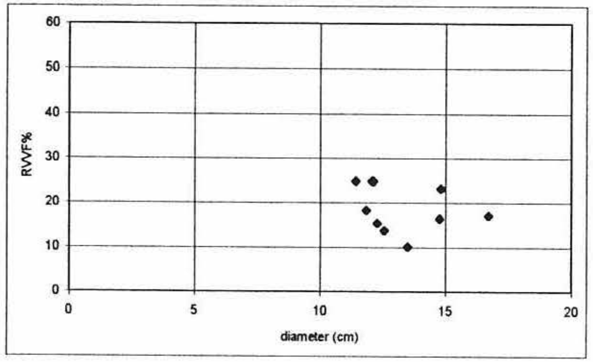


Appendix 3 - Relationships between the variables in trees of each seed origin

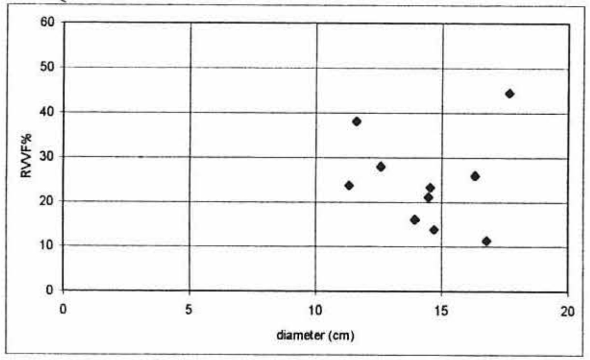
10RD-AL



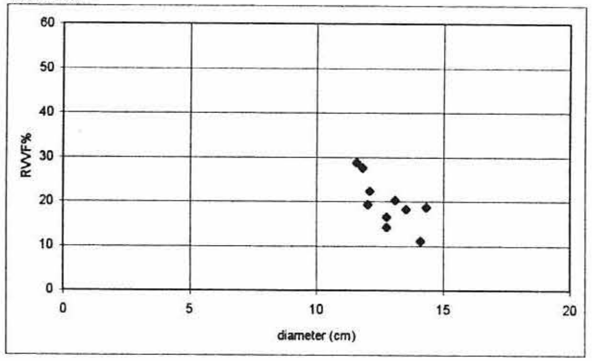
10RD-BC



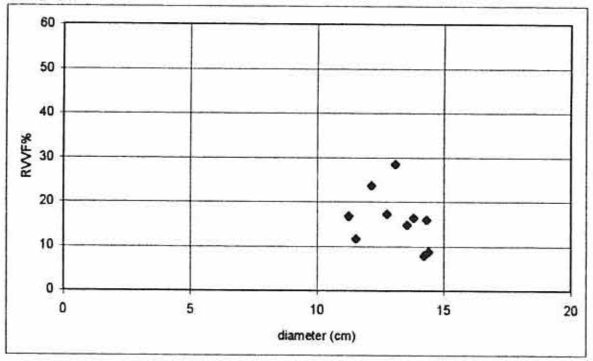
10RD-QCI



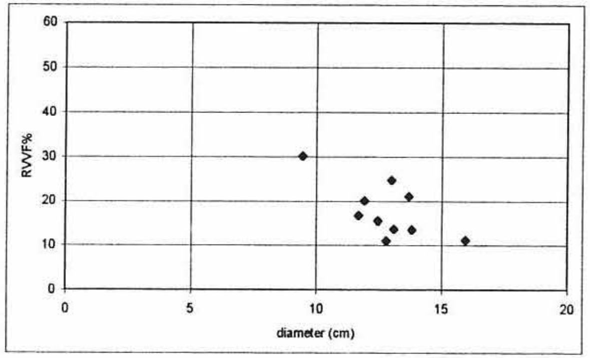
10RD-NW



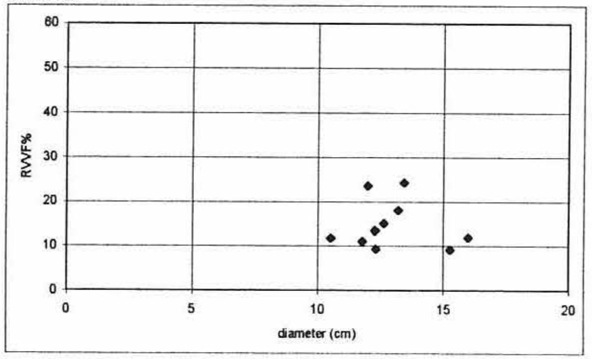
10RD-SW



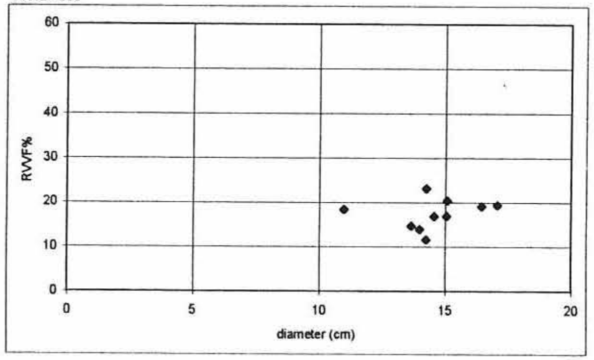
10RD-NO



10RD-SO

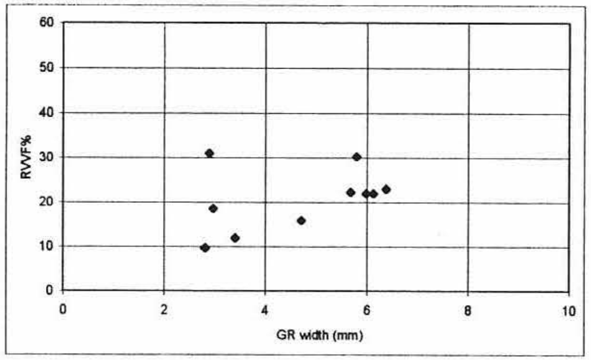


10RD-CA

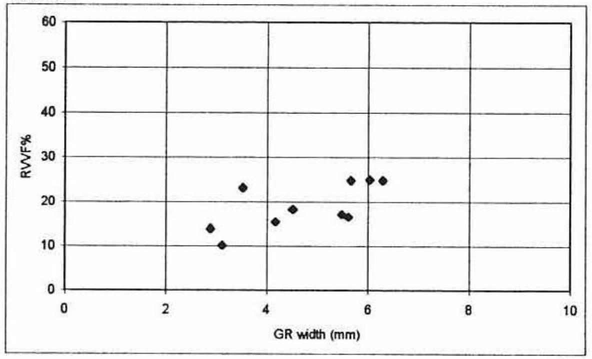


Appendix 3 - Relationships between the variables in trees of each seed origin

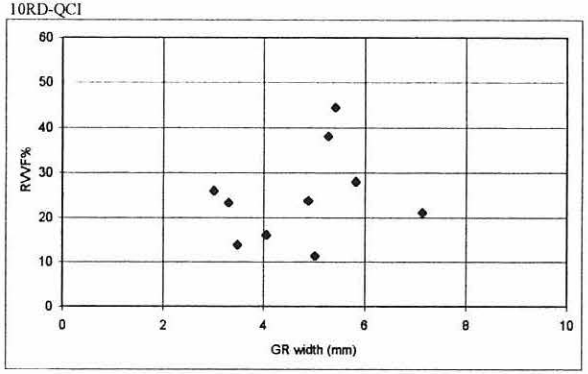
10RD-AL



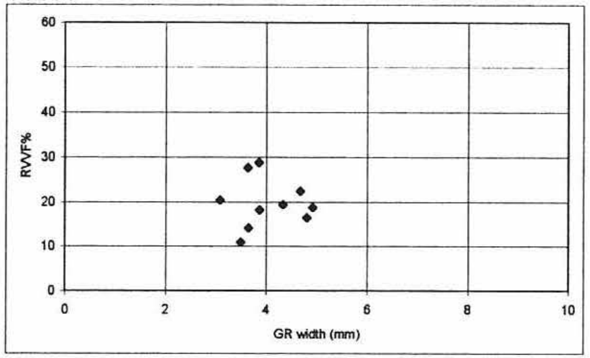
10RD-BC



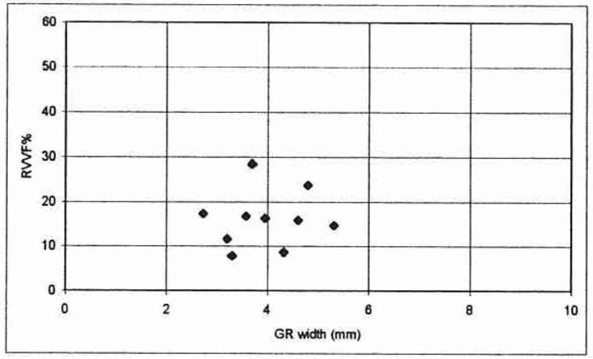
10RD-QCI



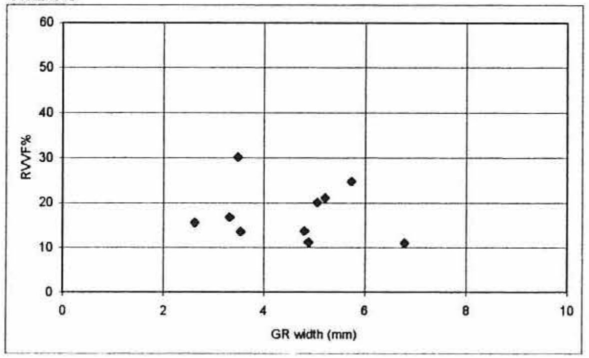
10RD-NW



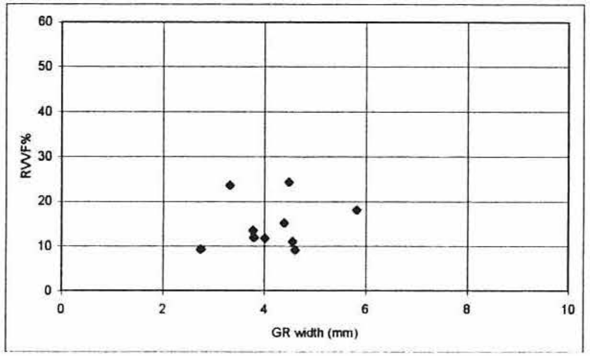
10RD-SW



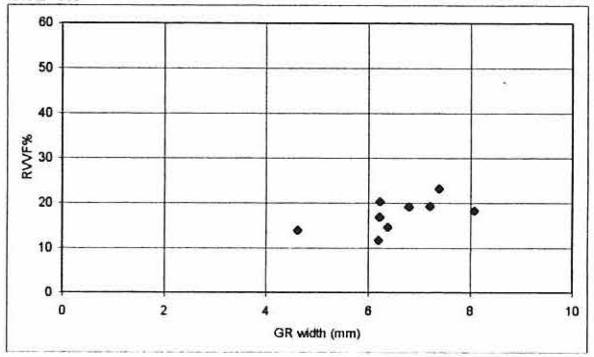
10RD-NO

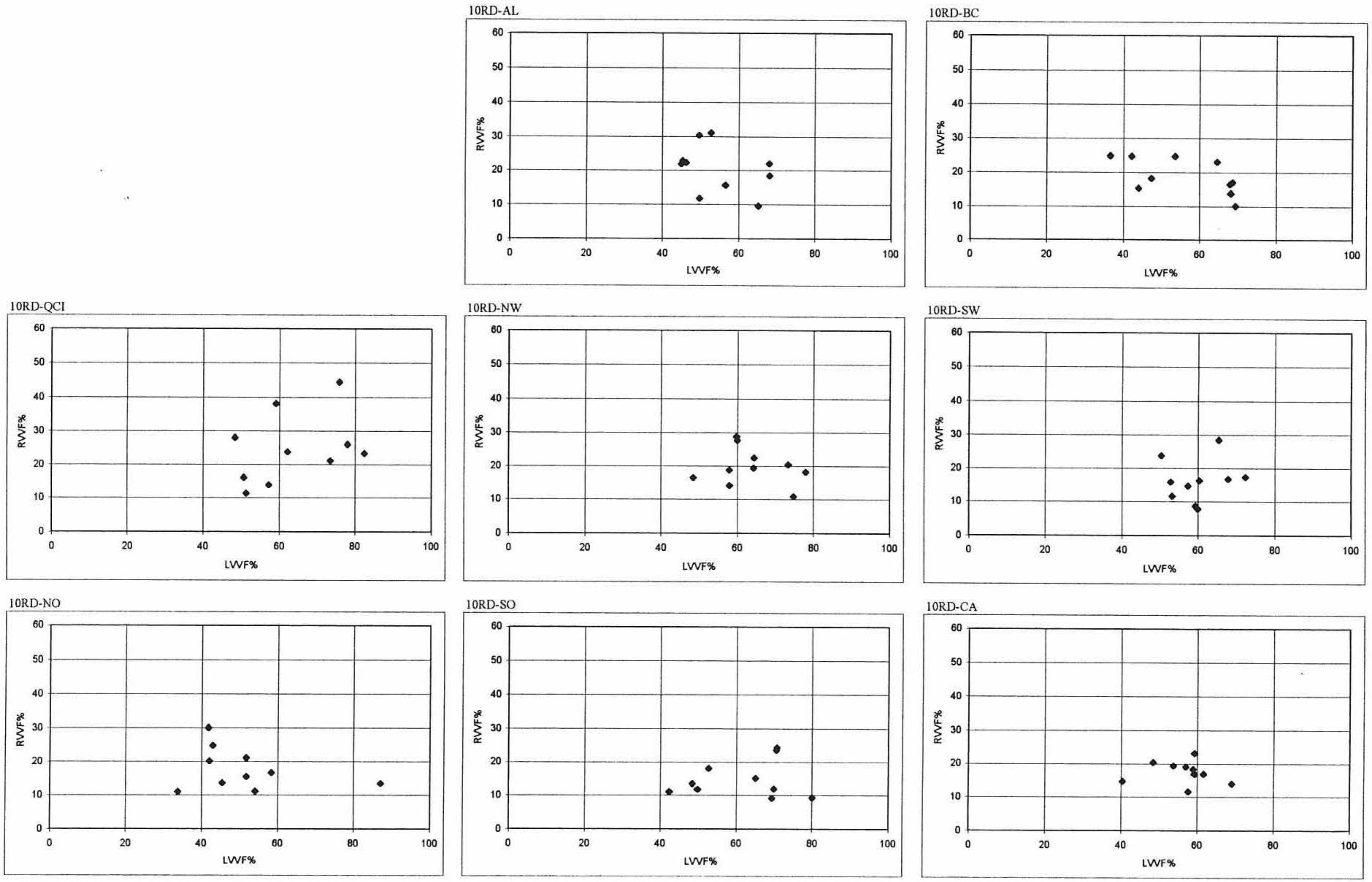


10RD-SO



10RD-CA





Appendix 3 - Relationships between the variables in trees of each seed origin