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Effects of Seed Origin and Site on Wood Density of Sitka Spruce (*Picea sitchensis* (Bong.) Carr.) Grown in Britain

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Abstract: Since density may have a direct influence on wood properties and because density is a factor under genetic control, this study details the effects of seed origins and sites on density. In addition to seed origins, its variability both within and between trees was also examined. In this case, the variation in density was investigated in eight seed origins of Sitka spruce (Alaska-AL, British Columbia-BC, Queen Charlotte Islands-QCI, North Washington-NW, South Washington-SW, North Oregon-NO, South Oregon-SO, and California-CA) grown at two sites in Britain (Dalby: Eastern England and Rhondda: South Wales). For this purpose, the five trees of each seed origin at each site were sampled at three heights (1, 2, and 3 m above ground level). It was observed that wood density decreased with increasing 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.

Key Words: Seed Origin, Site, Wood Density, Sitka Spruce, Plantations.

Tohum Orijini ve Yetişme Ortamının Britanya'da Yetiştirilen Sitka Ladini (*Picea sitchensis* (Bong.) Carr.)'nin Özgül Ağırlığı Üzerine Etkileri

Özet: Bu çalışmada, ağaç malzeme özelliklerini doğrudan etkileyen, genetik kontrol uygulamalarında önemli bir belirleyici olarak tanımlanan özgül ağırlığa farklı tohum orijinlerinin ve yetişme yerlerinin etkileri ile ağaçların dikili durumda yerden yüksekliklerine göre örnek ağaçlar arasındaki özgül ağırlık değişimleri araştırılmıştır. Bu çerçevede, Sitka ladini (*Picea sitchensis* (Bong.) Carr.)'ninde özgül ağırlık değişimi, Britanya'da iki farklı deneme alanında (Dalby: Doğu İngiltere, Rhondda: Güney Galler) yetiştirilen sekiz ayrı tohum orijini (Alaska-AL, British Columbia-BC, Queen Charlotte Islands-QCI, North Washington-NW, South Washington-SW, North Oregon-NO, South Oregon-SO, California-CA) üzerinde incelenmiştir. Deney örnekleri, her iki deneme alanında mevcut her bir tohum orijininden seçilen beşer adet ağacın toprak seviyesinden 1. 2. 3. m'deki yüksekliklerinden alındı. Araştırma sonuçlarına göre; özgül ağırlık, yıllık halka genişlemesine bağlı olarak, ağacın yerden yüksekliğinin artmasıyla azalmıştır. Ayrıca, her iki yetişme yerindeki tohum orijinlerinden NW, SW ve NO ağaçları ile Güney Galler bölgesindeki Rhondda yetişme yerinde yetişen QCI ve SO ağaçlarının, yavaş gerçekleşen çap artımı ve boyuna büyüme özellikleri nedeniyle diğerlerine göre daha yüksek, buna karşılık hızlı büyüme özelliği nedeniyle her iki yetişme yerindeki CA ağaçlarının ise en düşük özgül ağırlık değerlerine sahip oldukları belirlenmiştir. Bu nedenle, özgül ağırlık değerini yeterli düzeyde sağlayan QCI, NW, SW ve NO tohum orijinlerinin gelecekteki ağaçlandırma çalışmalarında kullanılması, yetersiz büyüme özellikleri nedeniyle her iki yetişme yerindeki AL ve CA tohum orijinlerinin ise kullanılmaması önerilmiştir.

Anahtar Sözcükler: Tohum Orijini, Yetişme Yeri, Özgül Ağırlık, Sitka Ladini, Yetiştirme.

Introduction

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) which can be controlled by genetic and silvicultural means (Denne and Dodd, 1980). Variation in wood quality makes it difficult to predict precisely the performance of timber and therefore process and utilise it efficiently. 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. In this case, 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/seed origin 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 in the UK) for Sitka spruce (the most commonly planted species in Britain) in order to recognise and in due course to breed from those trees combining high yield and good timber quality (Fletcher, 1976).

The timber of Sitka spruce grown in Britain is used particularly in the more financially rewarding construction industry. However, much of this plantation growth is light in weight for constructional purposes and it would be improved by an increase in earlywood density (Zobel and Van Bujitenen, 1980). Density (the dry mass contained in a volume of wood) is directly related to other properties and, therefore, is important as an index of wood quality (De Zeew, 1965). According to Brazier (1967), selection of trees reaching an adult condition for fibre length, density and 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.

Since it is a measure of the mass contained in a certain wood volume, density is also important as an index of quantitative production. This aspect is of interest to industries making products such as pulp, paper and fibre-board, as well as for the production of wood in a forest. Density is considered one of the most important indices of timber strength properties as it has been positively correlated with such properties as modulus of rupture (MOR) and modulus of elasticity (MOE) (Bendtsen, 1978), maximum crushing strength (Moulds, 1952), hardness and shrinkage (Brunden, 1964), and it also has a considerable influence on machinability, conversion, acoustic properties, and wearability (Fielding, 1967). These density variations have also been indicated for effects on permeability (McQuire, 1975).

Density is of key importance in forest product manufacture because it has a major effect on both the yield and quality of fibrous and solid wood products (Wilson and White, 1986) and because it can be changed by silvicultural manipulation (Williams and Hamilton, 1961) and genetic manipulation (Zobel, 1964). Differences in wood density between trees of various seed origins grown at the same site are dependent on the site (environmental) conditions that control the growth rate of the seed origins as a result of the properties of the soil (fertility, depth and moisture retention) and the climate (temperature, photoperiod, light intensity and rainfall), which are both significantly affected by altitude (Larson, 1969). Environmental conditions change during the life of a tree and, therefore, they affect both between and within tree variation. Since density may have a direct influence on some wood properties and because it is a factor under genetic control, this article details the effects of seed origins on density. The work described in this paper forms part of a larger study of the influence of genetic and environmental factors on the amenability of Sitka spruce to preservative treatment. The objective of this part of the study was to examine genotype x environment interactions in wood density of 8 seed origins grown at two sites in Britain. In addition, its variability both within and between trees and between sites was examined. Interactions of density between seed origins and sites were examined using analysis of variance, rank correlations and regression analysis (Finlay and Wilkinson, 1963).

Materials and Methods

The study was carried out on 80 twenty-year-old trees from eight seed origins of Sitka spruce grown at two experimental sites: Rhondda in South Wales and Dalby in North-East England (Figure 1). All the trees (a total of 40 trees from each site) were growing in a IUFRO (International Union of Forest Research Organisation) seed origin trial planted in 1975 when plots representing 34 (Rhondda) and 64 (Dalby) seed origins were laid down. The two sites represent extremes of the range of sites on which this species is used in Britain, and were chosen for this reason. Each site was laid out in a randomised block design with three blocks and 9 (3 x 3) trees per square plot. The planting density (spacing) was 2 m x 2 m. The soil type at Rhondda is *Molinia/Calluna* bog with carboniferous sandstone, however, is ironpan, with soft limestone at Dalby. Furthermore, both elevation and rainfall are higher at Rhondda (450 m, 2400 mm/year) than at Dalby (183 m, 835 mm/year).

The eight seed origins (Alaska-AL, British Columbia-BC, Queen Charlotte Islands-QCI, North Washington-NW, South Washington-SW, North Oregon-NO, South Oregon-SO, and California-CA) from throughout the whole distribution of Sitka spruce from north to south were chosen for this study (Table 1, Figure 1).

The selected trees were felled at 0.5 m above ground level and the 3 m log above this was marked to assist in identification (ISO 4471, 1982). Three discs 5 cm thick were cut from each tree at 1, 2, and 3 m above ground level. Each disc was marked with a code which identified site, seed origin, tree and position in the tree. The selected trees were then sampled by means of a 15 mm plug from the cross-section of the discs (Figure 2). The four plug samples 15 mm in diameter and 50 mm in length were produced longitudinally (in the stem direction) from each disc using a core forming drill. Each core was then kiln dried to 12 percent moisture content. From one end of each longitudinal core, thin samples 3 mm thick were cut and taken to be used for density determinations in accordance with the maximum moisture content method.

The method of determining density was used in this study based on the maximum moisture content method, which has been evaluated by Smith (1954) and adopted in both the British (BS 373, 1957) and American (ASTM D-2395, 1969) standards. In this method, 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. The standard method of assessment indicates that the wood block is fully saturated by distilled water prior to oven drying. The saturation is intended to measure the green volume according to the Archimedes principle, which states that a body immersed in a fluid experiences an upthrust equal to the weight of the fluid displaced. Thus a completely saturated wood block displaces an amount of water which equals its own volume. After having performed this procedure, the density of the experimental samples was calculated from the following equation:

$$d = [Mo / (Mo / G) + (Ms - Mo)] \times 1000 \qquad (1)$$

where d is the density of wood sample (kgm^{-3}), Mo is the oven dry weight of the sample (g), Ms is the weight of the sample saturated with deionised water (g), and G is the specific gravity of cell wall substance (i.e., taken to be 1.53 $g\ cm^{-3}$) (Bamber and Burley, 1983).

Results

It was observed that the overall mean of tree diameter at breast height (1.3 m above ground level) varied from 13.0 cm with Alaska (AL) to 16.5 cm with Queen Charlotte Islands (QCI) followed by 16.2 cm in California (CA). Mean growth ring width on the experimental samples ranged from 3.6 mm to 5.8 mm among the seed origins. In this case, the seed origin North Washington (NW) showed the narrowest ring width, whereas CA showed the widest growth ring width. This was therefore reflected in wood density, which was greatest in NW (434 kgm^{-3}), and lowest in CA (366 kgm^{-3}). The tree growth spread also differed significantly ($p \leq 0.05$) among seed origins at both sites. The mean tree diameter at breast height varied from 12.2 cm to 17.6 cm at Dalby, and 13.8 cm to 15.9 cm at Rhondda. At both sites, the seed origin AL had the narrowest tree diameter while the widest was QCI at Dalby and CA at Rhondda. Mean growth ring width was largest in seed

Table 1. Geographical locations of the trial seed origins

Region	Seed Origin	No*	Latitude (N)	Longitude (W)	Elevation (m)
Alaska	Duck Creek, Juneau Area	3024	58° 37`	134° 58`	30
British Columbia	Inverness, Prince Rupert	3044	54° 20`	130° 25`	0 - 30
Queen Charlotte Islands	Masset (Commercial Seedlot)	7111	54° 00`	132° 00`	0 - 15
North Washington	Forks, Olympic Rain Forest	3003	48° 07`	124° 30`	120 - 140
South Washington	Raymond, Willapa Bay	3009	46° 68`	123° 87`	15 - 30
North Oregon	Necanicum	3012	45° 82`	123° 77`	45
South Oregon	Brookings, Oregon	3018	42° 25`	124° 38`	90
California	Crescent City, California	3020	41° 67`	124° 18`	10 - 15

* IUFRO seed identification number

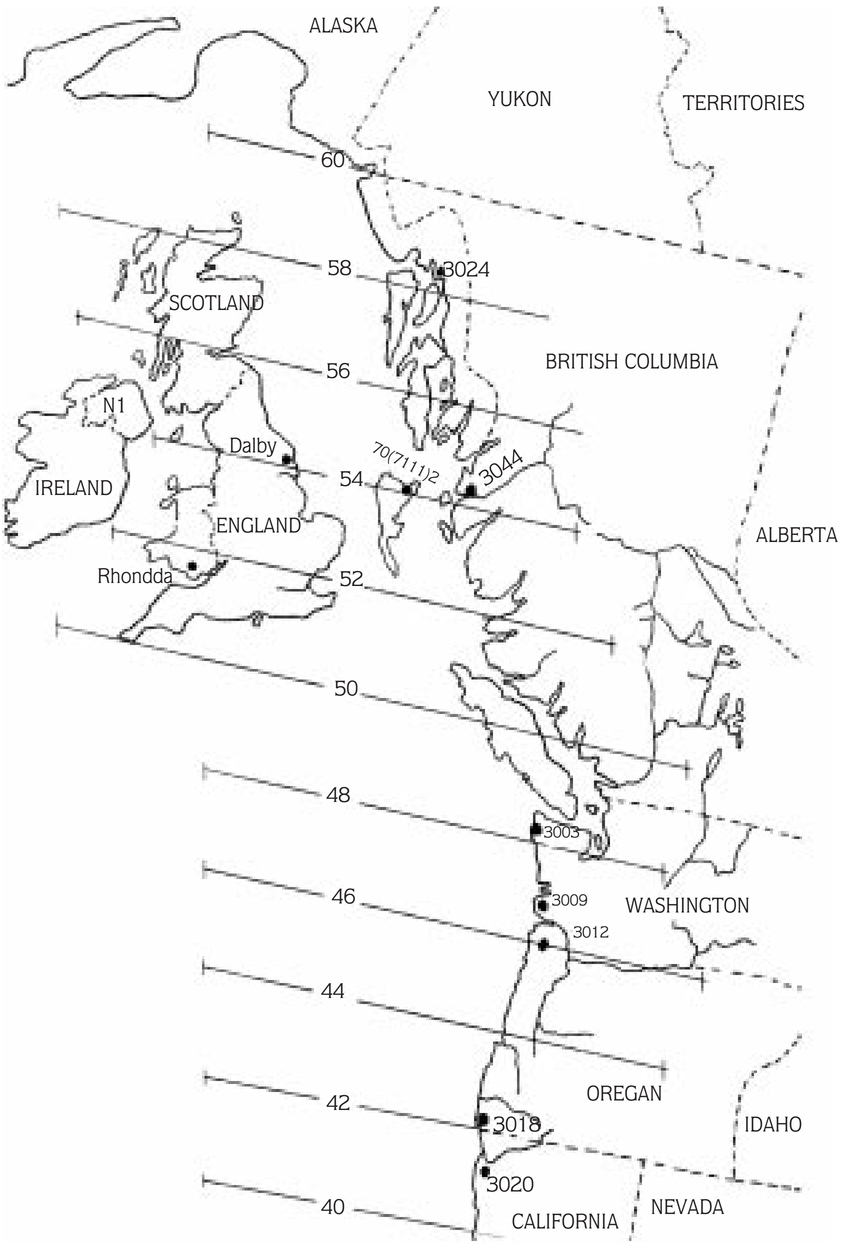

Figure 1. The geographical locations of selected seed origins (shown as in IUFRO seed identification number) on natural distribution of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) from southern Alaska to northern California, and the locations of trial sites in Britain: Dalby (in North-East England) and Rhondda (in South Wales).

origin CA at both sites (Dalby: 5.6 mm, Rhondda: 6.1 mm). On the other hand, the narrow growth ring occurred in different seed origins, i.e. the growth ring width was 3.1 mm in AL (Dalby) and 3.9 mm in NW (Rhondda). It was also observed that the total amount of latewood directly influenced density values. The seed origins AL (Dalby) and South Oregon (SO) (Rhondda), which of both had the highest amount of latewood, also had the greatest density (AL: 449 kgm^{-3}, SO: 458 kgm^{-3}), whereas CA, which had the lowest amount of latewood, also had the lowest wood density at both trial sites (Dalby: 361 kgm^{-3}, Rhondda: 371 kgm^{-3}).

According to the overall means of density (Figure 3), the results generally indicate that the material from

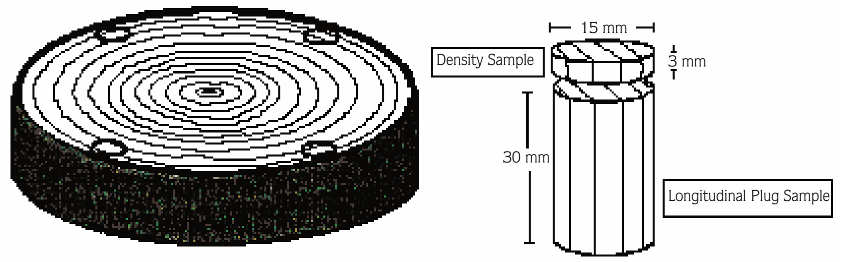

Figure 2. Locations of the experimental plug samples on the cross-section of the discs.

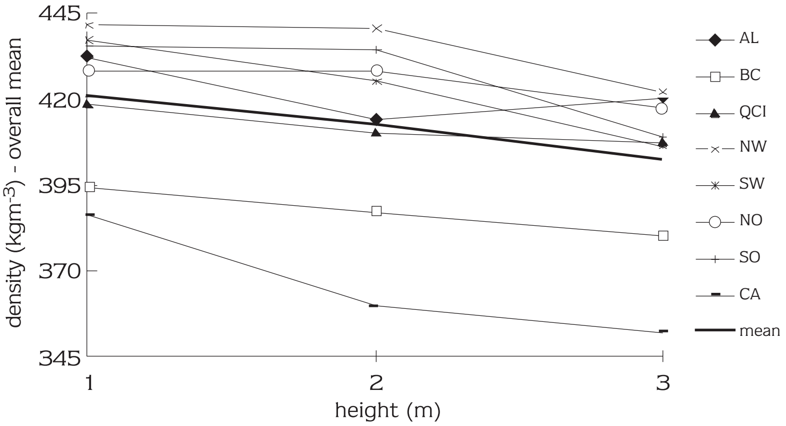

Figure 3. The vertical variation of density in each seed origin on overall means.

Washington (NW, SW) and Oregon (NO, SO) seed origins had higher densities while both British Columbia (BC) and California (CA) had lower densities.

The highest density occurred in NW followed by SO, NO and SW, whereas low densities were found in CA and BC. Although the densities of AL and QCI were notably greater than those of either BC or CA, they were slightly lower than those of NW, SO, NO and SW. The seed origin CA was highly significantly different from all of the other seed origins having the lowest density. BC had the second lowest density and also differed from the others. It also seemed that although the difference in density between QCI and NW was statistically significant, there were no significant differences between the other seed origins.

Means for density, tree diameter (at breast height: 1.3 m), and growth ring width of each seed origin grown at Dalby and Rhondda are given in Table 2 (with the indication of significance in density between the seed origins within the trial sites). There were significant differences (p=0.035) in density between the trial sites: it was lower at Dalby (408 kgm^{-3}) than at Rhondda (416 kgm^{-3}).

It seemed that the highest density at Dalby was in AL followed by NO and NW, whereas it was in SO followed by NW and SW at Rhondda. The descending order of density for the remaining seed origins also showed different patterns at both sites, e.g., the range at Dalby was SW, QCI and SO, but at Rhondda it was QCI, NO and AL. Despite this, the lowest density was in CA after BC at both sites. It was found that the average density of AL at Dalby and SO at Rhondda was significantly higher than that of all the other seed origins but only the differences in density between AL and NO (at Dalby), SO and NW (at Rhondda) were not statistically significant.

At Dalby: CA was significantly lower than all the seed origins. BC was significantly lower than both in NO and NW. Density in NO was significantly higher than both in QCI and SO. There was a significant difference between NW and SO. Although NW and QCI may appear to be different to each other, this difference was not found to be statistically significant.

At Rhondda: the difference between BC and CA was not statistically significant. NW, SW and QCI were significantly greater than AL and BC. Density of NO was significantly different from that of the seed origins SO, QCI, NW, BC and CA. Density in NO was significantly lower than in SO, QCI and NW but significantly greater than in BC and CA.

Table 2. Means of density, diameter and growth ring width in each seed origin at both sites.

Seed origins	Density (kgm^{-3})			Diameter at 1.3 m (cm)		Growth ring width (mm)	
	mean	(S.D.)		mean	range	mean	S.D.
Dalby							
AL	449.3	(±26.1)	a	12.2	11.8 - 14.9	3.1	±0.67
BC	391.4	(±48.1)	b	15.4	13.2 - 18.0	3.5	±0.84
QCI	400.5	(±43.6)	bc	17.6	15.4 - 19.5	3.6	±0.83
NW	421.7	(±48.7)	cd	15.1	14.5 - 16.0	3.5	±0.53
SW	415.0	(±34.0)	bcd	14.6	12.5 - 16.0	3.2	±0.54
NO	430.2	(±33.9)	ad	14.0	11.5 - 17.5	3.3	±0.66
SO	393.9	(±53.5)	b	14.8	13.2 - 17.0	3.5	±0.67
CA	361.3	(±11.1)	e	16.5	15.7 - 18.3	5.6	±0.88
average	407.9				15.0		3.7
Rhondda							
AL	394.3	(±28.3)	ac	13.8	12.0 - 14.8	5.4	±0.17
BC	382.3	(±21.6)	a	14.7	13.6 - 17.4	5.0	±0.47
QCI	422.3	(±45.8)	bd	15.4	13.0 - 18.4	4.9	±0.88
NW	446.6	(±47.8)	be	14.4	13.7 - 14.9	3.9	±0.34
SW	430.2	(±39.6)	bd	14.8	12.7 - 16.4	4.1	±0.72
NO	418.6	(±30.3)	cd	15.3	14.2 - 15.8	5.1	±0.77
SO	458.1	(±30.4)	e	14.0	12.6 - 15.5	4.2	±0.68
CA	371.2	(±17.3)	a	15.9	12.4 - 18.1	6.1	±0.45
average	415.6				14.7		4.8

∇ Means of density and growth ring width shown here are of data from 5 trees per seed origin and 3 heights per tree at each trial site, but that for diameter is at 1.3 m height from the trial trees.

∇ Pairwise differences between seed origins at both sites were observed for basic wood density by using the Tukey Comparison Test after having performed one-way analysis of variance.

∇ Means of density that are not significantly different from each other at $P<0.05$ level have the same letters in a given column (e.g., in Rhondda, BC 382,8a is not significantly different to CA 371,2a).

∇ The average densities of sites are significantly different from each other at $P<0.05$ level.

Interactions between seed origins and sites are highlighted by ranking origins in descending order of density from highest to lowest at each site (Figure 4).

It was found that seed origins were individually denser at one site than the other and the descending order of the densities varied between the sites. The mean densities of the Rhondda trees of SO, NW, SW, QCI and CA were significantly higher than those of the Dalby trees, whereas the seed origins of AL, NO and BC were less dense at Rhondda than at Dalby. In addition, BC and CA showed lower densities at both sites.

Discussion

Comparing the results of density at the different heights, it appears that density declines with increasing height in stem corresponding to a trend of increasing ring width from 1 m to 3 m (Figure 5), and since these trends were common to all trees at 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).

The overall trends of the vertical variation in wood density within trees that were observed in the analyses were consistent with those established for spruces by previous researchers (Brazier, 1970; Denne, 1979; Harvald and Oleson, 1987; Simpson and Denne, 1993; Mitchell and Denne, 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 1 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 3).

As noted by Harvald and Oleson (1987) and Saranpaa (1994), density usually decreases with height in Sitka spruce. This was true in all seed origins except the trees

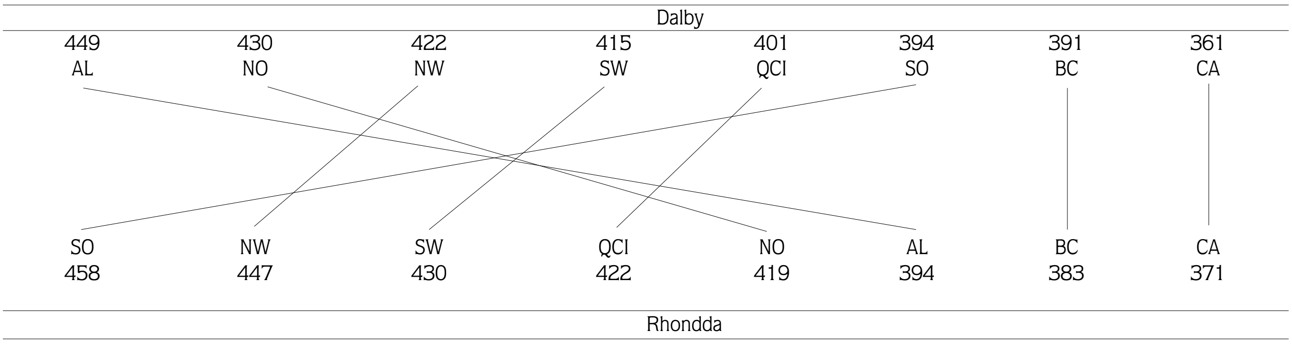

Figure 4. Interactions Site x Seed Origin for density.

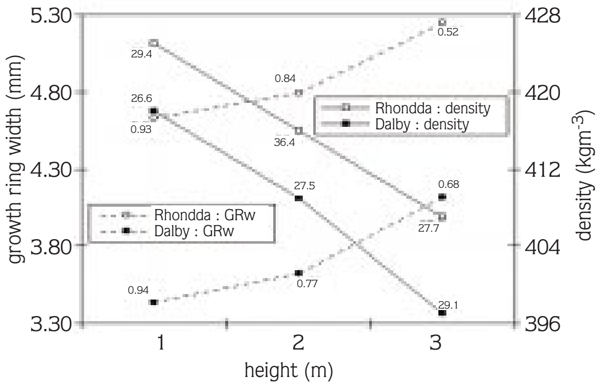

Figure 5. Comparison of changes in growth ring width (GRw) and wood density at both trial sites. The values on data points represent the standard deviation of the means at each height.

of AL, QCI, NW and SO (at Dalby), and AL and NO (at Rhondda). In general, there was a minor increase in density between 1 m and 2 m in both NW and SO at Dalby, and between 2 m and 3 m for the remaining seed origins (Figure 6). Similar findings were reported by Spurr and Hsiung (1954).

In many previous investigations of Sitka spruce, mean tree density tends to be inversely correlated with the growth rate of the tree (Brazier, 1967; Harvald and Oleson, 1987; Maun, 1992). 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 accounted for 30%, and radial tracheid diameter plus wall thickness 66% of the variation in mean tree density. Likewise, linear regressions between the trees in our study showed that density in Sitka spruce was less correlated with ring width (accounting for only 27.3% of the variation). It was also found that density was more correlated with ring width at Rhondda than at Dalby, accounting for 50.5% and 38.0% respectively. Tree diameter also accounted for a small variation (20.1%) in density between trees at the Dalby site.

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). Thus, for example, trees of NW, SW and NO at both sites, SO at Rhondda, AL at Dalby had higher than average mean densities, and trees of BC and CA at both sites, AL at Rhondda, and QCI and SO at Dalby had a lower than average density. However, trees of NW and SO at Rhondda, and AL and NO at Dalby had lower than average growth rates for their sites (Figure 7).

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 at Rhondda, and AL and NO at Dalby had the highest wood density due partly to their slower rates of growth, and CA at both sites had the lowest density on account of its rapid growth.

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

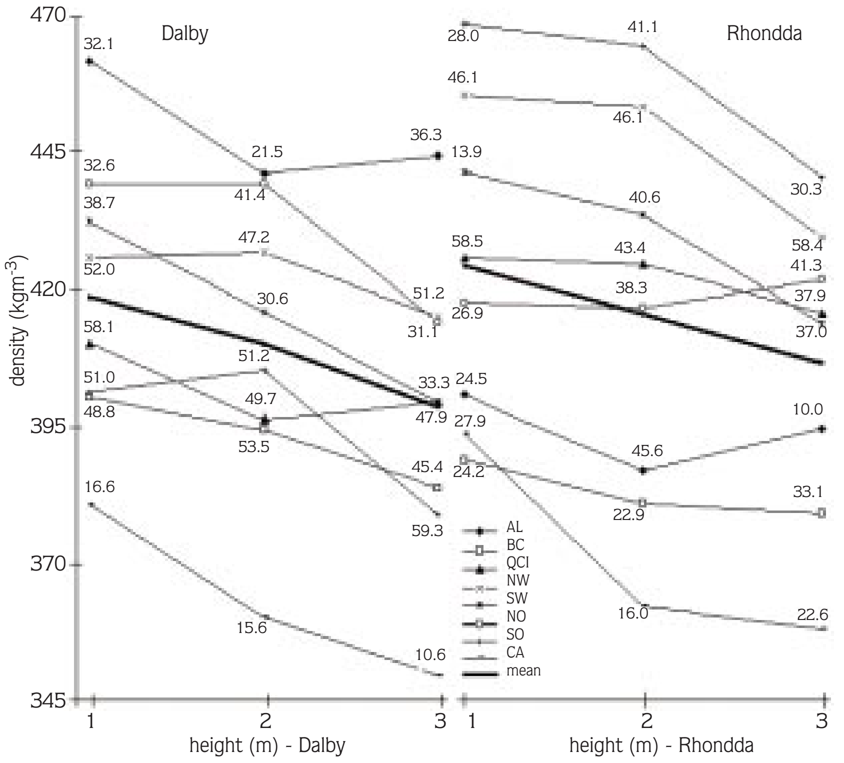

Figure 6. Vertical variation in density in each seed origin at both trial sites. The values on data points represent the standard deviation of the means at each height.

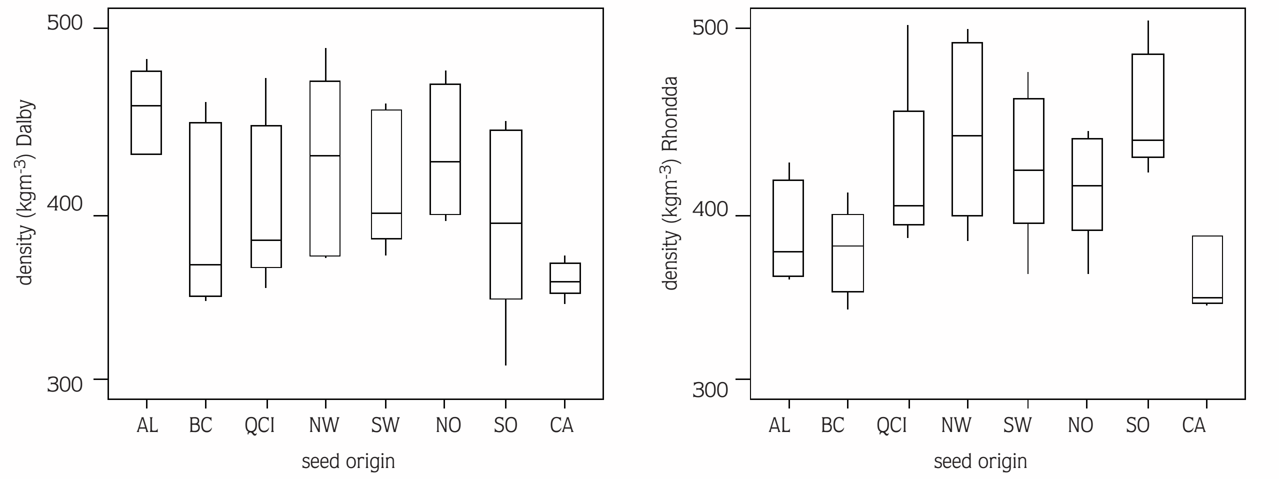

Figure 7. Boxplot[1] showing the density distribution of trees of each seed origin at the trial sites.
[1]Boxplots are also called box and whisker plots. The box shows the distance between the quartiles, with the median marked as a line, and the whiskers show the extremes (Bland, 1995).

genotypes to produce wood of adequate density under the UK conditions tested.

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 at these two sites, significant differences were evident in ring width: it was greater at Rhondda than at Dalby, probably as a result of a higher rainfall at Rhondda (2400 mm/year) than at Dalby (835 mm/year).

As mentioned by Fletcher (1992), the results of IUFRO seed collection experiments in 1969/70 have indicated that seed origins from Queen Charlotte Islands (QCI) were good general purpose sources which were reasonably frost hardy, resistant to exposure and produce acceptable timber. Furthermore, seed origins from Washington (NW and SW) and Oregon (NO and SO) could be used with increases in timber production but with the possibility of a slight decrease in strength properties. In our study, the trees originating from CA (at both sites) 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 2). Further, as it was initially shown by Lines (1987), it was also found in our study that seed origins AL and BC grew poorly at both sites. It may be therefore suggested that these two seed origins should be avoided in future plantations. However, QCI, NW, SW and NO should be selected for more plantations as all grow well with a good density (Figure 8). On the other hand, CA at both sites and SO at Dalby showed the fastest growth but low density. It should be possible to select for individuals with high volume 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, a typical example of this is QCI.

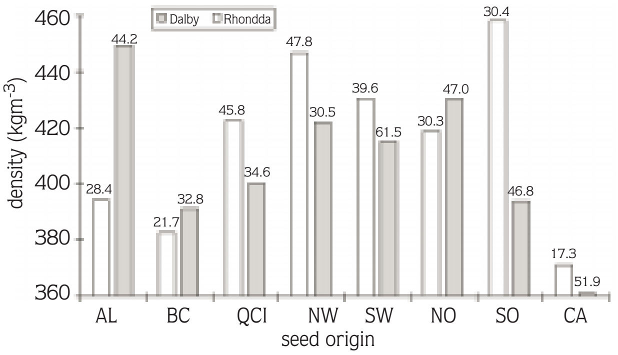

Figure 8. The variation of density between trial seed origins at both sites. The values on data bars represent the standard deviation of the means in each seed origin.

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