Effects of genetics on the wood properties of Sitka spruce growing in the UK: bending strength and stiffness of structural timber

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Summary

Mechanical tests were conducted on structural timber from a 37-year-old Sitka spruce (*Picea sitchensis* (Bong.) Carr), progeny trial located in Kershope Forest, Cumbria, UK. Values of modulus of rupture (MOR) and global modulus of elasticity (MOE_G) in bending and density were compared between timber cut from four of the eight different seed lots which made up the experiment. Three of these seed lots were open-pollinated progeny of selected plus trees, while the fourth consisted of trees grown from an unimproved collection imported from the Queen Charlotte Islands (QCI) in British Columbia, Canada. The progenies from the plus trees were selected for their contrasting growth rates, stem form and wood density relative to the QCI control. Overall, the timber had characteristic values for density, MOR and MOE_G consistent with the requirements for the C16 strength class. A significant difference in timber basic density was observed between two of the seed lots; however, there was no difference in MOR or MOE_G between any of the seed lots. Most of the variation in strength properties in the study was attributable to differences between individual trees (≈40 per cent) and individual pieces of timber from within a tree (≈50 per cent), with only a small amount (≦5 per cent) due to treatment differences. Results indicate that gains in merchantable log volume that have been achieved due to tree breeding do not appear to have been offset by a reduction in the mechanical properties of timber.

Introduction

Due to its ability to grow on a wide range of sites, coupled with a growth rate exceeding that of other conifers in this country, Sitka spruce (*Picea sitchensis* (Bong.) Carr) is the most widely planted commercial conifer species in the UK (Brazier, 1970; Joyce and OCarroll, 2002). Currently, the total area planted in this species is ~730 000 ha (Forestry Commission, 2007). Some 80 per cent

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of the predicted doubling in the UK's wood production by 2020 will be due to an increased outturn of Sitka spruce (SFIC, 2004). Therefore, it is important for the profitability of the UK's forest industry that home-grown Sitka spruce can gain increased acceptance as a structural timber, as the markets for non-structural end uses such as pallets, packaging and fencing are close to saturation (McIntosh, 1997). For construction uses, three of the key timber quality criteria are dimensional stability (i.e. low distortion), strength (modulus of rupture (MOR)) and stiffness (modulus of elasticity (MOE)) (Kliger *et al.*, 1994). These properties, particularly strength and stiffness, are in turn related to other properties including wood density, knot size, spiral grain and microfibril angle (Cave 1968; Cave and Walker, 1994; Walker, 2006), which have varying degrees of heritability (Rozenberg and Cahalan, 1997).

The need to produce good quality sawn timber has been recognized by Sitka spruce tree breeders whose main objective has been 'to develop breeding populations well adapted to a range of site types, with improved stem form and growth potential and wood qualities satisfactory for the sawn timber market' (Fletcher and Faulkner, 1972). The UK's tree improvement programme for Sitka spruce began in 1963 with the selection of 'plus trees' that had a combination of superior height, diameter, stem straightness, branching quality and low external grain angle. Approximately 1800 such trees were selected over the following 20 years from stands consisting of material grown from seed that was believed to have originated from the Queen Charlotte Islands (QCI), which are located off the coast of British Columbia, Canada (Lee, 1999). This origin of seed was commonly planted in the UK because early results from provenance tests indicated that it was the most suitable for the bulk of Sitka spruce planting sites (Samuel *et al.*, 2007). Progeny testing has been used to determine the relative genetic value of these selections, and progenies from all 1800 plus trees were tested in groups of 50 in 200 tests established across a range of sites between 1967 and 1993 (Lee, 1999). From these tests, the heritability of the various traits as well as the genetic correlations between traits are being determined (Lee, 1999). This information is being used to estimate the breeding value of each plus tree for the economic traits of interest (i.e. diameter, stem form and wood density).

These values will then be combined, with appropriate weightings, to generate a multi-trait index value for each progeny, and plus trees will then be ranked according to the index value of their progeny (Lee, 2001). This approach will be used to develop the General Breeding Population consisting of the best 240 plus trees, while the best 40 of these plus trees will be reselected to form the production population. In order to produce trees that yield a greater proportion of structural timber capable of meeting the requirements for the C16 and possibly the C24 strength classes as defined in EN338 (CEN, 2003a), tree breeders have proposed two additional production populations: (1) a high wood density production population and (2) a high stem straightness production population.

While tree breeders have assumed that increasing the wood density and reducing branch size will increase the proportion of timber satisfying the requirements for the C16 (and possibly the C24) strength class, there have not been any studies that have compared the mechanical properties of timber from genetically improved Sitka spruce with those of timber cut from unimproved QCI trees. Timber properties have only been compared between four different Sitka spruce provenances growing in Ireland (Treacy *et al.*, 2000). This study found that the MOE of timber did not differ between the selected provenances but that the MOR of timber from the Californian provenance was significantly lower than from the Washington provenance.

In 2004, the opportunity arose to fell a mature tree breeding trial and to make detailed measurements on a number of characteristics on the standing trees and logs and then to measure the density, microfibril angle and the mechanical properties of structural timber and small defect-free wood samples cut from the trees. This trial was chosen because it consisted of large plots, each containing sufficient mature trees to represent all the individual treatments including the QCI control, which can often suffer badly later in the rotation due to competition from faster growing trees in adjacent plots (Lee, 1992). The primary purpose of this study was to compare the properties of timber cut from the progeny of selected plus trees with those of timber from an unimproved QCI seed lot and to gain a better understanding of the distribution of these properties within and between trees. This paper presents the results from static bending tests undertaken on Sitka spruce structural timber from different seed sources and tests the null hypothesis that mechanical properties and grade out-turn do not differ between timber produced from progeny of three Sitka spruce plus trees and trees grown from an unimproved QCI seed lot. Comparisons of microfibril angle, wood density and the mechanical properties of small defect-free wood samples will be presented in a companion paper (McLean *et al.*, 2009), while more detailed information on log and timber out-turn is presented in Mochan *et al.* (2008).

Materials and methods

Experimental site

Trees sampled in this study were taken from a trial established in subcompartment 13 of Kershope Forest, Cumbria, UK (latitude 55° 05′ N, longitude 2° 50′ W, elevation 190 m). The trial was established in 1968 by Forest Research's Tree Improvement Branch and consisted of trees raised from open-pollinated seed collected from seven different plus trees selected at various locations in the UK, as well as an unimproved QCI seed lot which served as a control. All eight seed lots were planted across the site in a mix of plot sizes and shapes ranging from single-tree plots through to 12-tree row plots and square plots consisting of between 2 × 2 and 6 × 6 trees. Trees were planted at 1.8 m square spacing and there were three complete replications of all combinations of seed lot and plot size across the site. The experiment was never thinned.

Thirty-five years after planting, the diameter at breast height (d.b.h.) of all surviving trees in the 4 × 4, 5 × 5 and 6 × 6 square plots was measured (Forest Research, unpublished data). Analysis of these data indicated no significant difference or interaction between plot size and diameter, and therefore, all trees in the three different plot sizes were combined to form a single replicate within a block. The outerwood density of every standing tree in each seed lot was assessed using a Pilodyn gun which measures the depth of penetration of a pin fired with a fixed force (Raymond and MacDonald, 1998). Stem straightness was also assessed on these trees using the seven-point scoring system developed for use in Sitka spruce (Macdonald *et al.*, 2001). Because resources for the study did not allow trees from all treatments to be felled and processed, only the QCI control and three other open-pollinated seed lots were selected. The three open-pollinated seed lots chosen represented a vigorous seed lot (Family 3), a straight seed lot (Family 2) and a seed lot with higher wood density (Family 4) (Table 1). It was thought that these seed lots would represent the range of progenies which might be available to breeders from their extensive network of progeny tests (Lee, 2001) and each could potentially form the basis of future improved planting stock. Hereafter, these three open-pollinated seed lots and the QCI control are referred to as treatments.

Sampling

Twelve trees with d.b.h. greater than or equal to 18 cm were randomly sampled from each replicate of each of the four different treatments (with one additional tree sampled in the QCI control), giving a total of 145 trees. This lower limit on d.b.h. ensured that all logs cut had a small-end diameter of at least 16 cm, which is the minimum requirement for structural sawlogs in the UK (Forestry Commission, 1993). Trees selected for detailed study were felled and their total height and heights to the lowest live branch and lowest live whorl were measured. Diameter over bark was also measured at 1-m intervals up the stem

Table 1: Comparison of growth, form and wood density of the seven families relative to the QCI control

Open-pollinated family	Improvement in characteristic expressed as a percentage difference relative to the QCI control		
	Growth (%)	Straightness (%)	Wood density (%)
1	+5	−15	−10
2	+7	+20	−8
3	+7	+12	−4
4	−3	+22	+7
5	−4	−2	−5
6	+6	+4	−5
7	0	−5	−2

and these data were used to calculate total stem volume. Felled trees were then cut into 3.1-m logs, with up to five logs cut from each tree; however, in most cases, the number of logs cut from each tree was less due to poor stem form, excessive branch size or diameter restrictions. These logs were classified as either ‘green’ or ‘red’ according to the UK softwood grading rules (Forestry Commission, 1993), which are based on sweep and branch size. For a log to be classified as green (the better grade), 80 per cent of its branches had to be less than 50 mm in size and the sweep could not exceed 10 mm per metre of length (i.e. 31 mm for a 3.1-m log). Red logs are those which have sweep in excess of 10 mm per metre of length but less than 15 mm m^{-1} and/or more than 20 per cent of their branches greater than 50 mm in size. Overall, a total of 268 logs were cut from the 145 trees (Table 2), and all these were classified as green. These logs were processed into 646 pieces of structural timber (nominal cross-sectional dimensions of 100 × 47 mm) using standard sawmill cutting patterns for the size of log. Each piece of timber was uniquely coded so that it could be related back to a specific log and tree. Most of the sawn timber was cut from the bottom two log height classes, i.e. log midpoint height was less than 7.2 m (Table 3). All timber was kiln dried to 20 per cent moisture content in a conventional temperature kiln as a single load.

Material testing

The timber was then randomly divided into two subsamples, both of which contained at least one piece of timber from each log. The first subsample was visually strength graded, while material in the second subsample was machine strength graded with a Computermatic MK5B grading machine using a C16/reject setting in accordance with EN519 (CEN, 1995a). All timber was then stored in a controlled environment chamber at 20°C and 65 per cent relative humidity until it attained constant mass, with a corresponding equilibrium moisture content of ~12 per cent.

All 646 pieces of timber were mechanically tested in the laboratory. Four-point bending tests were conducted on each piece of timber using a Zwick Z050 testing machine (Zwick Roell, Ulm, Germany). This was done according to the procedures described in EN 408 (CEN, 2003b), with the exception that the timber specimens were bent about their minor axis as the intention was to compare results with those obtained from

Table 2: Distribution of logs cut from the 145 trees in the Kershope experiment

Treatment	Number of trees	Number of logs	Number of logs by relative position within a tree				
			First log	Second log	Third log	Fourth log	Fifth log
QCI	37	56	32	18	6		
Family 2	36	82	31	24	19	8	
Family 3	36	66	31	19	9	6	1
Family 4	36	64	35	23	5	1	
Total	145	268	129	84	39	15	1

Table 3: Number of specimens of timber produced by treatment and by log height class.

Treatment	Log height class (m)				Total
	0–3.6	3.7–7.2	7.3–10.8	>10.8	
QCI	61	47	23	3	134
Family 2	88	59	38	18	203
Family 3	70	59	24	19	172
Family 4	76	49	10	2	137
Total	295	214	95	42	646

the strength-grading machine. However, approximately half the specimens were tested to failure by bending them about the major axis. The moisture content of each specimen immediately prior to testing was measured using a resistance moisture meter (Protimeter Timbermaster, GE Sensing, Billerica, MA, USA).

The global modulus of elasticity (MOE_G) of each piece of timber was calculated using the data from the four-point bending tests through the following relationship:

$$MOE_G = \frac{a^2(s-2a)^2(F_2-F_1)}{3Is(w_{s2}-w_{s1})}, \quad (1)$$

where $F_2 - F_1$ is an increment of load in the linear region of the load-deflection curve (N), $w_{s2} - w_{s1}$ is an increment of deflection corresponding to $F_2 - F_1$ (mm) a, c and s are the span distances (mm) shown in Figure 1, I is the second moment of area of the timber specimen ($I = bd^3/12$) (mm^4) and b and d are the breadth and depth of the test piece, respectively. The deflection used to calculate MOE_G would normally be that of point E relative to points D and F (Figure 1). However, there were not enough deflection sensors available to allow the deflection of point E to be measured simultaneously with the other deflection measurements. Therefore, $w_{s2} - w_{s1}$ was calculated from the deflection of the loading head and $w_{c2} - w_{c1}$ and the geometry of the testing set-up using the following relationship:

$$w_{s2} - w_{s1} = (w_{x2} - w_{x1}) + (w_{c2} - w_{c1})\left(\frac{L}{c}\right)^2, \quad (2)$$

where $w_{x2} - w_{x1}$ is an increment of movement of the loading points corresponding to $F_2 - F_1$ (mm). Following testing, a 40-mm long sample spanning the full cross-section of the sample was cut from each piece of timber and both bulk density and basic density were calculated from the mass and volume of this sample using the procedures described in Simpson (1993). MOE_G was adjusted to a 12 per cent moisture content basis using the procedure described in EN384 (CEN, 1995b).

Assignment of timber to a strength class

The characteristic values of MOE, bending strength and density for each of the four treatments were calculated using the procedures described in EN384 (CEN, 1995b). The characteristic values for both MOE and density were equal to the mean values obtained from measurements on the timber from each treatment, while the characteristic value for bending strength was calculated from the 5th percentile of MOR values obtained for each treatment. In accordance with EN384 (CEN, 1995b), these values were multiplied by 0.8 on the basis that bending strength was assessed for at least 60 pieces of timber from each treatment (i.e. $k_s = 0.8$). For the entire population of 646 pieces of timber, the value of this factor was increased to 0.9 (i.e. $k_s = 0.9$). Because the timber had been machine strength graded, the 5th percentile values were also multiplied by 1.12 to reflect the lower variability of machine-graded timber (i.e. $k_v = 1.12$). Based on these

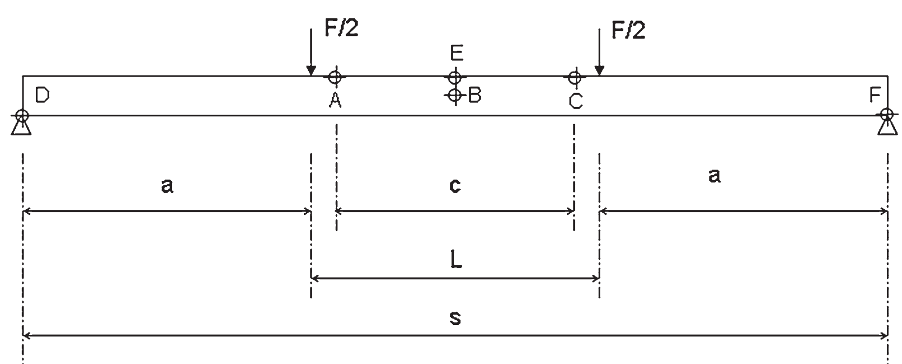

Figure 1. Schematic diagram showing the position of supports and points of load application for the four-point bending tests to measure MOE and MOR.

characteristic values, timber was assigned to a strength class based on the requirements given in EN338 (CEN, 2003a). Provided that the characteristic values of bending strength and density for a particular strength class were met, the characteristic value for bending stiffness only needed to exceed 95 per cent of the required value for that strength class. For the C16 strength class, provided that the characteristic bending strength and the bulk density (at 12 per cent moisture content) exceed 16 N mm^{-2} and 370 kg m^{-3}, respectively, the mean MOE has to be at least 7.6 kN mm^{-2}. The differences in these characteristic values and the resulting strength grade between treatments were compared.

Data analysis

Data were analysed using the open source statistical package R (www.r-project.org). A linear mixed-effects model (Pinhero and Bates, 2000) was used to compare basic density, MOE_G and MOR between treatments. A nested structure was assumed for the random effects of log, tree, plot and block in accordance with the experimental design. The following model was fitted to data from the measurements on the structural timber:

$$y_{ijklmn} = \mu + \tau_i + B_j + P_{k(j)} + T_{l(jk)} + L_{m(jkl)} + e_{n(jklm)},$$

where y_{ijklmn} is the measurement of basic density, MOE_G or MOR on an individual specimen, μ is the overall mean, τ_i is the fixed effect of the ith treatment ($i = 1, 2, 3, 4$), B_j is the random effect of block j ($\sim N(0,\sigma_B^2)$), $P_{k(j)}$ is the random effect of the kth plot within the jth block ($\sim N(0,\sigma_P^2)$), $T_{l(jk)}$ is the random effect of the lth tree within the kth plot ($\sim N(0,\sigma_T^2)$), $L_{m(jkl)}$ is the random effect of the mth log within the lth tree ($\sim N(0,\sigma_L^2)$) and $e_{n(jklm)}$ is the random effect of the nth piece of timber from the mth log ($\sim N(0,\sigma_e^2)$). The model was also used to quantify the amount of variation in basic density, MOE_G and MOR associated with each strata (i.e. block, plot, tree, log, etc.) by omitting the fixed effect of treatment. Tree-level data, such as d.b.h. and stem volume, were also analysed using the same statistical model, but in these analyses, the random effects associated with intra-tree variation were omitted. Differences between treatments were examined using F tests, and all tests were made at alpha = 0.05 level of significance. The assumptions of linear models, particularly those relating to homogeneity of variances, were tested and where appropriate transformations were made. Ordinary least squares regression was used to investigate relationships between the timber properties.

Results

Growth characteristics and timber yield

The maximum d.b.h. of sampled trees was 42.2 cm, with an overall mean of 23.9 cm. There was suggestive but inconclusive evidence to indicate that there was a difference in the d.b.h. of sampled trees between treatments ($F_{3,6} = 4.42$, $P = 0.058$) with Family 4 having a smaller mean d.b.h. than Family 3 (Table 4). However, this did not translate into a difference in mean stem volume of sampled trees between treatments ($F_{3,6} = 1.68$, $P = 0.269$). There was a higher yield of structural dimension timber from three improved families compared with that from the QCI control (Table 5). In particular, the number of pieces of structural timber cut per unit tree basal area and per unit tree volume were 50 per cent and 59 per cent higher, respectively, for Family 2 than for the QCI control.

Physical and mechanical wood properties

There was a 100 per cent pass rate for the sub-population of timber that was machine strength graded to C16. Basic density of the whole population of timber ranged from 272 to 426 kg m^{-3}, with a mean of 348 kg m^{-3} (Table 6). Values of MOE_G ranged from 4.0 to 12.0 kN mm^{-2}, with a mean of 7.9 kN mm^{-2}. There was no relationship between MOE_G and basic density (R^2 = 0.08). Values of bending strength (MOR) ranged from 16.7 to 65.4 N mm^{-2} and there was a direct relationship with MOE_G (R^2 = 0.41; Figure 2) but not basic density (R^2 = 0.12). The mean value of MOR for the population of 646 pieces of timber was 35.0 N mm^{-2} and the characteristic strength (based on the 5th percentile value) was 16.7 N mm^{-2} (Table 6). Characteristic strength values for a particular treatment should be treated with

Table 4: Sample and stand-level characteristics (mean values) of the four treatments selected for further measurement

Treatment	Sample tree characteristics					Stand-level characteristics			
	d.b.h. (cm)	Height (m)	HLB* (m)	HCB (m)	Tree volume (m^3)	d.b.h. (cm)	Yield Class	Stand density (trees/ha)	Basal area (m^2 ha^{-1})
QCI	23.5	23.5	14.9	16.4	0.523	20.7^a	22	1559	56
Family 2	24.7	28.8	15.7	17.0	0.562	22.2^b	24	2097	84
Family 3	25.5	24.6	15.4	16.6	0.604	22.2^b	24	1913	79
Family 4	2.1	23.9	15.0	16.5	0.479	19.9^a	22	2012	66

Figures with different superscript alphabets are significantly different at $P \leq 0.05$. No superscripts indicates significance tests either not carried out or no differences were found between any of the treatments. Stand-level data are from Mochan *et al.* (2008).

* HLB and HCB are the height to the lowest live branch and height to the lowest live whorl, respectively.

Table 5: Comparison of the yields of 100 × 47 × 3100 mm dimension timber per unit standing tree volume and basal area between treatments

Treatment	Basal area (m^2)	Tree volume (m^3)	Timber yield per unit basal area		Timber yield per unit tree volume	
			Pieces m^{-2}	Relative to QCI (%)	Pieces m^{-3}	Relative to QCI (%)
QCI	1.69	19.35	79	100	7	100
Family 2	1.71	18.51	119	150	11	159
Family 3	1.87	21.13	92	116	8	117
Family 4	1.39	17.26	99	124	8	114

Values presented are for all sampled trees in each treatment.

Table 6: Comparison of mean values of density, MOE_G and MOR, and the characteristic bending strength between treatments

Treatment	Basic density (kg m^{-3})	Bulk density at 12% m.c. (kg m^{-3})	MOE_G (kN mm^{-2})	MOR (N mm^{-2})	
				Mean	Characteristic value
QCI	350.5^{ab} (3.8)	433.1^{ab} (5.2)	8.2^a (0.27)	33.9^a (1.78)	16.7
Family 2	344.8^{ab} (3.5)	425.3^{ab} (4.7)	8.0^a (0.26)	34.5^a (1.63)	19.2
Family 3	339.2^a (3.7)	417.7^a (5.0)	7.7^a (0.27)	34.1^a (1.74)	17.6
Family 4	359.8^b (3.7)	445.7^b (5.0)	7.6^a (0.26)	39.3^a (1.74)	22.6
Overall	348.6	425.7	7.9	35.5	20.0

SE of the means are given in parentheses. Means followed by a different superscript alphabets are significantly different at $P \leq 0.05$.

caution as fewer than 100 samples of timber were tested for each treatment. Based on the characteristic values of density (adjusted to a 12 per cent moisture content basis), MOE_G and MOR, the overall sample of timber met the requirements for the C16 strength class. Timber from each of

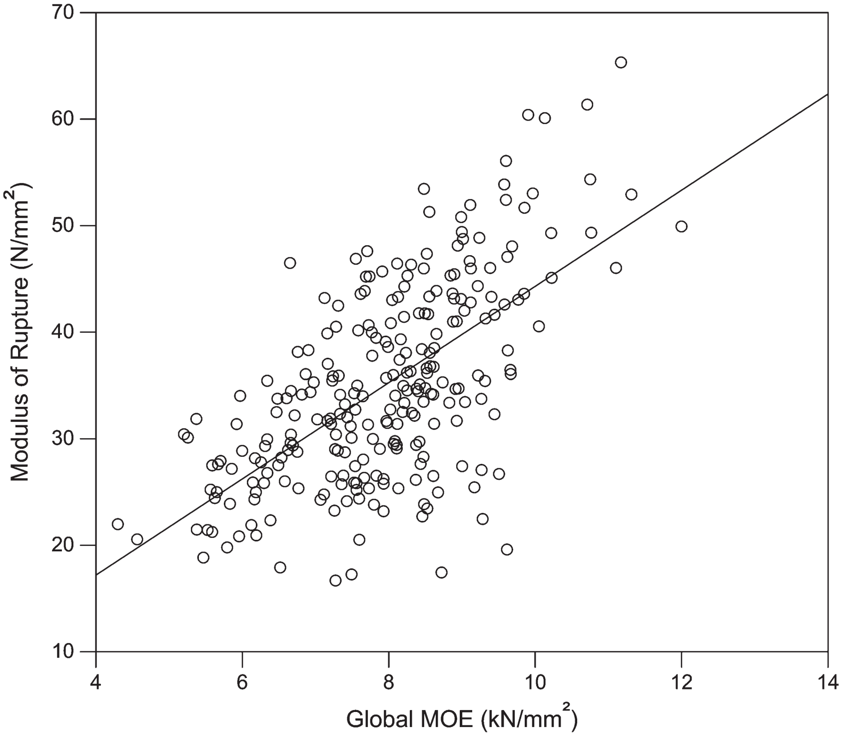

Figure 2. Relationship between MOE_G and bending strength (MOR). The solid line was fitted using ordinary least squares regression.

the four treatments also met the requirements for the C16 strength class, but timber from Family 4 only just satisfied the stiffness requirement despite having the highest characteristic bending strength (Table 6).

Intra- and inter-treatment variation in timber properties

There was a significant difference in the mean basic density of timber between treatments ($F_{3,6} = 5.7$, $P = 0.034$). Timber from Family 4 had significantly higher density (~20 kg m^{-3}) than timber from Family 3 ($P = 0.008$) but not timber from the QCI control ($P = 0.130$; Table 6). While statistically significant differences were found between treatments, this factor only explained 4.1 per cent of the variation in basic density. Most of the variation was attributable to individual trees within each treatment (41.0 per cent) and to differences between individual pieces of timber from within a log (50.8 per cent). There was no difference in MOE_G between treatments ($F_{3,6}$ = 2.0, $P = 0.216$). Again, only a small amount of the variation in MOE_G was attributable to treatment (0.6 per cent), while most of the variation was attributable to individual trees within a treatment (38.4 per cent) and individual pieces of timber within a log (50.5 per cent). There was no difference in the MOR of timber between treatments ($F_{3,6}$ = 2.81, $P = 0.130$) with most of the variation due to tree-to-tree differences within a treatment (49.4 per cent) and to differences between individual piece of timber within a log (47.3 per cent).

Discussion

While there was a significant difference in basic density of the timber cut from Family 4 compared with Family 3, this did not translate into higher bending strength or stiffness. McLean (2008) found that two of the three improved families appeared to have a slightly higher microfibril angle in the juvenile core (i.e. the first 10 annual rings from the pith) than the QCI trees (McLean, 2008). This was most pronounced for Family 4, which also had the highest wood density. Overall, the trend in MOE between treatments more closely mirrored the trend in microfibril angle than the trend in wood density.

The study found that the two main sources of variation in density, MOE and MOR of structural timber were random tree-to-tree variation within a treatment and differences between individual pieces of timber from within a log. These differences were much greater than differences between treatments. The high level of tree-to-tree variation is likely to be partly due to the fact that trees in each treatment were grown from seed collected from open-pollinated trees (i.e. they were half-sib as only the mother tree was known). It would be expected that this source of variation would have been considerably less if this study had been conducted in a trial containing clonal material or even trees grown from seed collected from control-pollinated trees (i.e. full-sib material where both parents are known). The magnitude of tree-to-tree variation within a treatment also indicates that there is considerable scope to improve wood quality through tree breeding. The current tree breeding programme has focussed on increasing density, reducing branch size and improving stem straightness as the main means of improving wood quality (Lee, 1999). Because Sitka spruce timber generally fails to meet the requirements for the C24 strength class because of insufficient stiffness rather than insufficient strength and because wood stiffness in this study was only just sufficient to meet the requirements for the C16 strength class, it would be worth considering trying to breed trees with higher stiffness, possibly through selecting trees with a low microfibril angle or by screening trees in the breeding population using portable acoustic tools (e.g. Matheson *et al.*, 2002; Kumar, 2004). Studies conducted in radiata pine (*Pinus radiata* D. Don) have found that there is significant genetic variation in juvenile wood microfibril angle (Donaldson and Burdon, 1995) and that this variation is greater than in the outerwood zone (Walker and Butterfield, 1995). Microfibril angle in juvenile wood is thought to have a significant heritability (Donaldson and Burdon, 1995) and hence, there is scope for selecting trees for lower microfibril angle in order to improve the stiffness of juvenile wood. Given that much of the Sitka spruce structural timber produced in the UK is cut from the juvenile core of the tree, any improvement in the stiffness of timber coming from this region of the tree is likely to lead to improved grade out-turn.

The largest source of variations in density, MOE and MOR in this study was between specimens of timber from within a log. This is not unexpected as there are strong radial trends in both density and microfibril angle (Walker, 2006). In Sitka spruce, density near the pith is relatively high and decreases until a minimum is reached between 10 and 15 growth rings from the pith before increasing again with increasing distance from the pith (Kennedy, 1995; B. Gardiner, J.-M. Leban, J. Hubert, P. Denne, in preparation). Microfibril angle decreases rapidly from an angle of 40°–50° near the pith before reaching an angle of ~10° at around age 15–20 years and is thereafter more or less constant (McLean, 2008). Because MOE is related to density and microfibril angle (Cown *et al.*, 1999; Evans and Ilic, 2001), there is a corresponding increase in MOE from pith to bark. Many of the specimens tested in this study were cut from near the pith. This is the region of the tree which contains juvenile wood (corewood) with a high microfibril angle and low wood stiffness (Burdon *et al.*, 2004). Therefore, timber cut from this part of a log would be expected to have a lower MOE than that cut from nearer to the outside of the log (Kliger *et al.*, 1995; Walker and Butterfield, 1995). If such timber can be segregated out of the population, the average MOE should increase.

Overall, while there was a lack of difference observed in the mechanical properties of structural timber between the different treatments, there were considerable differences in the recoverable volume of sawn timber. In particular, Family 2 could yield up to 60 per cent more structural timber per unit tree volume than the QCI trees. This increase in productivity is important as forest management in the future will be for multiple objectives, not just timber production. This could result in increased species diversity as well as a wider range of management intensities (Mason, 2007). If the area within the forest estate dedicated to timber production decreased, an increase in productivity on those areas still intensively managed for timber production could maintain a stable Sitka spruce timber supply. The results from this study indicate that increases in out-turn from planting improved stock are achieved without a reduction in timber mechanical properties.

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Conflict of Interest Statement

None declared.

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