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The Effects of Site and Stand Factors on the Tree and Wood Quality of Sitka Spruce Growing in the United Kingdom

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The extent and sources of variation in the wood quality of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) were quantified using data collected from 64 stands in northern Britain. These stands were selected on the basis of elevation, latitude, longitude, yield class, initial spacing and the presence or absence of thinning. Dynamic modulus of elasticity (MOE) was calculated from measurements of stress wave velocity made on standing trees and qualitative descriptions were made of stem form. Dynamic MOE of individual trees ranged from 3.81 kN/mm^2 up to 12.29 kN/mm^2, with a mean of 7.71 kN/mm^2. Approximately 55 percent of the variation in dynamic MOE was due to differences between individual trees within a site, while 35 percent was due to differences between sites. The remaining 10 percent was due to differences between the measurements made on opposite sides of each tree. Variation in dynamic MOE at the site level was significantly influenced by yield class, elevation as well as by a number of the interactions between these factors and latitude, longitude and initial spacing. A multiple regression model incorporating these variables was able to explain 45 percent of the variation in dynamic MOE. Ramicorn branches were the most commonly recorded defect (37.2% of all live trees), followed by stem scarring and basal sweep (6.9% and 6.3%, respectively). Dynamic MOE was not influenced by stem straightness ($p = 0.10$) which indicates the utility of stress wave velocity measurements for segregating Sitka spruce stands based on potential grade recovery.

Keywords acoustics, timber properties, wood stiffness, wood quality
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1 Introduction

The commercial softwood wood products industry in the United Kingdom is largely based on Sitka spruce (*Picea sitchensis* (Bong.) Carr.). This species is native to the west coast of North America and was introduced into the UK in 1831 (Bryan and Pearson 1955). However, commercial plantings in the UK began in the 1920s, with large scale plantings undertaken in the 1950s and 1960s particularly in upland areas of England and Scotland (Mason 2007). Today, the total area of Sitka spruce plantations in the UK is approximately 730 000 ha (Forestry Commission 2007), with more than 75 percent of this plantation area being in Scotland and northern England. It is predicted that wood production from Scottish forests will increase by 2020 to approximately 10 million m^3 (SFIC 2004), with approximately 80% of this increase in production in Sitka spruce.

While the wood from Sitka spruce grown in the UK is used in the production of pulp and paper and panel products, the majority is sawn into timber. The three main uses for this sawn timber in the UK are construction, pallets/packaging and fencing (McIntosh 1997). Because the markets for non-structural end products such as pallets, packaging and fencing are either saturated or likely to become saturated in the future, it is important for the profitability of the domestic forest products industry that Sitka spruce can gain acceptance as a construction timber. While the yields of C16 grade construction timber from UK sawmills processing Sitka spruce are generally in excess of 90 percent, there is some concern that these yields could reduce in the future due to the perception that the quality of the round timber that will come from forests maturing in the next 20 to 25 years is lower than that of the current resource (Macdonald et al. 2009). These concerns are based on trends in the management of spruce stands which have taken place in the past 50 years, particularly the move to wider planting spacing in the late 1960s, the adoption of no-thin management, and the preference for mechanised and systematic thinning practices (Cameron 2002).

The move to wider planting spacing, in order to reduce establishment costs (Wardle 1967), would be expected to have a detrimental effect on timber properties as planting distance affects stem characteristics such as knot and branch size and wood density. This is supported by Brazier and Mobbs (1993) who found that a maximum initial spacing of 2 m by 2 m was required in order to achieve an acceptable yield of C16 grade timber in un-thinned Sitka spruce stands. The adoption of no-thin management provides no opportunity for improving stand quality. Similarly, the use of mechanised and systematic thinning practices reduces options for improving stand quality (Methley 1998). Therefore, historical data on the wood properties of Sitka spruce (e.g., Broughton 1962, Brazier et al. 1976) may not be characteristic of the current or future resource.

In addition to the effects of forest management, it is also expected that there will be variation in wood properties between stands of a similar age due to differences in climatic and soil factors. For example, Bryan and Pearson (1955) found that the density of Sitka spruce wood decreased with increasing latitude. Likewise, trees growing at higher elevation sites, which are generally more exposed, often have inferior stem form compared with those trees planted in more sheltered sites (Hubert et al. 2003) and may also contain wood which is less stiff than that found in trees growing on more sheltered sites (Telewski 1989). In order for the local wood processing sector to better utilise the resource and to plan future investment, they require information on the extent and sources of variation in wood properties. Such information would enable sawmills to determine the proportion of the resource that is potentially suitable for producing construction grade timber, as well as providing them with the ability to identify those stands based on site and management factors that are unlikely to produce construction grade timber. Wood from these stands could then be directed to another and more appropriate end product.

Studies to assess the extent and sources of variation in wood properties have been undertaken in a number of other countries, including several regions within Australia and New Zealand (e.g., Roper et al. 2004). A key element of these studies has been the use of portable acoustic tools which are able to predict wood stiffness from measurements made on standing trees (Wang et al. 2007). Wood stiffness (modulus of elasticity) is an important mechanical property of timber and is commonly the property that is measured when timber is machine strength graded. It is also the property that generally limits the strength grade that UK-grown Sitka spruce timber can achieve under EN338 (CEN 2003). Furthermore, wood stiffness is the key parameter for engineers when designing structures for the serviceability limit state under Eurocode 5 (CEN 2004). Previous research has shown that there is a strong relationship between standing tree measurements and the properties of timber cut from these trees (e.g., Wang et al. 2001). Therefore, information on the wood stiffness obtained from these instruments can be used to identify stands which would be unlikely to yield economically acceptable yields of construction timber.

Currently, there is very little information available on the extent and sources of variation in the wood properties of Sitka spruce growing in the UK and other factors which affect its suitability for producing construction timber. Therefore, an initial screening study was undertaken in order to: 1) quantify the magnitude of between and within-stand variation in wood stiffness calculated from measurements made using portable acoustic tools; 2) assess the nature and frequency of stem defects which can affect sawn timber recovery and potentially wood properties; and 3) identify those site and tree-level factors associated with the variation in wood stiffness and develop predictive models based on these factors.

2 Methods

2.1 Experimental Design

The study was undertaken in Scotland and northern England as these regions contain the majority of Sitka spruce grown in the UK. In addition, assessments of stem form had been undertaken at 469 sites in these regions as part of two earlier studies (Stirling et al. 2000, Mochan et al. 2001). As a result, good site and stand level information existed for these locations which allowed sites to be selected *a priori* for this study. In order to best capture the likely range in variation in wood properties and to examine the influence of silvicultural and site factors, stands were selected on the basis of the following attributes: 1) site productivity (as quantified by yield class), 2) elevation, 3) latitude, 4) longitude, 5) initial planting spacing, and 6) thinning history. In order to reduce any confounding influences of tree age on wood properties, the criteria that stands had to be between 35 and 45 years old was applied. This reduced the number of potential sites down to 204.

In order to investigate the impact of these factors and their interactions, a factorial design was proposed. However, to undertake this study as a 2^6 factorial experiment would have required 64 sites, before allowing for any replication. If each combination of factors was replicated twice, then the study would require 128 sites. Because a full factorial design is not very efficient when the number of factors is greater than five (Kuehl 1994), the study was undertaken using a fractional factorial design. In this study a half replicate of a 2^6 factorial was used, i.e., a 2^{6-1} factorial. This design had 32 combinations and allowed all the main effects, all the two-way and most of the three-way interactions to be tested. Each combination was replicated twice which was considered sufficient for an initial screening study such as this. This resulted in 64 stands being sampled. The levels for each factor were chosen based on the distribution of site and stand attributes from the 204 potential sites (Table 1). Each factor had two levels, with the boundary between the high and low levels for each quantitative factor corresponding to the median value (Table 1). In the case of thinning, this factor had two levels – thinned and un-thinned. The levels of each factor for each of the 32 combinations were selected using the experimental design function within Minitab (Minitab Inc., State College, PA). If there was more than two sites having the required combinations of attributes, two sites were randomly selected from the larger pool of potential sites. Where stands having the required combination of attributes could not be identified from the population of 204 sites from the stem form assessment study, additional sites were chosen from the Forestry Commission's sub-compartment database. In two instances, the stand age criteria had to be relaxed slightly in order to find suitable sites.

Table 1. Summary of site and stand factors used in the fractional factorial design, along with the definitions for the high and low levels of each factor.

Factor	Range	Median	Low level	High level
Yield class (m^3/ha/yr)	6–24	14	≤ 14	> 14
Elevation (m)	0–545	281	≤ 280	> 280
Latitude (deg/min)	54°36´–58°18´N	55°21´N	≤ 55°21´N	> 55°21´N
Longitude (deg/min)	2°06´–5°58´W	3°27´W	≤ 3°34´W	> 3°34´W
Initial spacing (m)	1.12–3.21	1.99	≤ 2.00	> 2.00
Thinning	-	-	Un-thinned	Thinned

2.2 Field Measurements

For each of the 64 selected sites, a circular 0.02-ha fixed area plot was installed with the plot centre located using a GPS at the same coordinates recorded for the original stem form assessment plot. If the location of the plot corresponded to an un-stocked area or contained large amounts of wind damage, the plot was moved to the nearest area of fully-stocked forest. If the site had been felled, another site with the same combination of attributes was randomly selected. Within each 0.02-ha plot, the diameter at breast height (DBH – 1.3 m) of all trees with DBH greater than 7 cm was measured and the stem form (straightness) of the bottom 6-m of all live trees was assessed using the seven-point scoring system developed by Methley (1998) and Macdonald et al. (2001). Other attributes of trees such as the presence of forks, broken tops, ramicorn branches (i.e., those branches with an angle of emergence from the stem of greater than 60° from horizontal), stem scarring (assumed to be as a result of animal damage or thinning operations), severe basal sweep, etc. were recorded using a series of qualitative codes (Table 2). Total height was measured on up to 16 trees per plot, however in many cases it was only possible to measure one or two trees per plot due to the relatively high stand densities resulting in the tops of the trees being obstructed from view. In a few cases it was not possible to measure the heights of any trees within a plot. Mean top heights were estimated for these stands from prior information on stand age and yield class using appropriate height-age functions (Rollinson 1999).

The stress wave velocity was measured on ten randomly selected trees from the population of live trees with DBH greater than 17 cm within each plot using a modified version of the IML Hammer (Instrumenta Mechanic Labor GmbH, Germany). The two probes from this instrument were inserted into the tree at a distance of 1 m apart in the vertical direction centred about breast height. Two sets of measurements were made on each tree: one on the north side and one on the south. Previous investigations (Forest Research, unpublished data) have determined that these orientations provide the most consistent measurements of acoustic velocity and this has been adopted as the standard in the UK. On each side of the tree, measurements were made until three consecutive measurements differed by less than 100 m/s. Once this occurred, the average of the three measurements was recorded. The longitudinal dynamic modulus of elasticity (MOE) of the outermost wood of each standing tree was calculated from the mean of the stress wave velocity measurements made on the two sides of the tree using the following equation (Wang et al. 2001):

$$\mathrm{MOE} = \rho V^2$$

where V is the stress wave velocity [m/s] and ρ is the density of green wood [kg/m^3]. The density of green sapwood was assumed to be 1000 kg/m^3 for all trees. A 12-mm diameter pith-to-bark core sample was taken from the north side of each of the 10 trees at breast height using the Trecor corer (CSIRO, Australia). These cores will be used for subsequent analysis to determine

Table 2. Qualitative codes used to describe various tree attributes, their definitions and frequency of occurrence.

Code	Description	Number of trees	Percentage of all live trees	Maximum occurrence within a plot (%)
CK	Crook in crown indicating recovery from past leader damage	3	0.2	7.1
DT	Dead, broken or defective top	29	1.5	22.2
ED	Edge tree located on edge of clearing or road	47	2.4	
FK	Forked, i.e. a tree with multiple leaders	55	2.8	19.1
LN	Severe lean (i.e., >15 degrees from vertical)	22	1.1	14.3
MF	Other type of malformation not described by existing qualitative codes	54	2.8	33.3
RB	Heavy external resin bleeding possibly indicating the presence of internal resin pockets in the wood	24	1.2	17.5
RM	Ramicorn branch – branch with an angle of emergence from the stem greater than 60 degrees from horizontal	728	37.2	88.0
SC	Stem scarring from lightning, logging or animal damage	180	9.2	84.6
SW	Basal sweep exceeding one-third of tree DBH	123	6.3	25.0
UH	Unhealthy – a tree carrying very few age classes of needles	117	6.0	26.1

microfibril angle and density using the Silviscan system (Evans and Ilic 2001). Where a tree was leaning, this core was taken from the side of the tree perpendicular to the direction of lean so as to avoid compression wood.

Climatic information for each site was obtained using the Ecological Site Classification system (Pyatt et al. 2001). This software contains interpolated climate surfaces that have been calculated for each 10 km grid square using data from the UK Meteorological Office for the period 1961–1990. Data on the accumulated temperature (number of days per year above a threshold of 5.6 °C), moisture deficit (maximum accumulated amount that monthly potential evaporation exceeds rainfall) and the Conrad Pollack continentality index were obtained from the location of each stand. The climatic zone for each site was determined from accumulated temperature and moisture deficit using the classification described in Pyatt et al. (2001). These zones range from warm dry through to alpine. The level of wind exposure (DAMS score) at each site was estimated from topographic variables using the approach developed by Quine and White (2003). Mean wind speed was predicted from DAMS score using the approach described in Quine (2000). Soil information for each site was obtained from available soil maps using standard Forestry Commission soil types (Pyatt 1970, 1982).

2.3 Data Analysis

Data were analysed using the R open-source statistical package (R Development Core Team 2007). The number of live and dead trees per hectare were calculated for each plot, along with the corresponding basal area of each fraction. The proportion of trees within each plot which have each of the descriptive codes listed in Table 2 was calculated. Variance components analysis was used to quantify the relative magnitudes of between-stand, within-stand and within-tree variation in dynamic MOE. The mean value of dynamic MOE was calculated for each site and ANOVA was used to determine whether this was related to the various site and stand factors and/or the interaction between these factors. In all analyses, an $\alpha = 0.05$ level of significance was chosen. A multiple regression model was then developed using the actual numerical values for those variables that were found to be significant from the ANOVA.

3 Results

3.1 Variation in Site and Stand Characteristics

The locations of the 64 sites sampled are shown in Fig. 1. There was a large number of sites in southwest Scotland (Dumfries and Galloway) and northeast England (Northumberland) which was due to the large area of Sitka spruce plantations found in these regions. The estimated accumulated temperature for these sites ranged from 760 up to 1425 day degrees >5.6 °C, while the moisture deficit ranged from 10.3 up to 130.2 mm. Based on the combination of these two factors, 42 sites were classified as being cool moist, 8 were cool wet, 9 were cool dry and the remaining 5 were warm dry. Site windiness as assessed by DAMS score ranged from 8.1 (least windy) up to 19.2 (most windy). These values corresponded to predicted mean wind speeds of 8.6 km/h up to 21.3 km/h.

A total of 2488 trees (1949 live and 539 dead) were measured across 64 sites, with an overall summary of the tree and stand-level attributes given in Table 3. While there was considerable variation in tree size and stand density, the mean DBH and height of individual trees was 230 mm and 22.1 m, respectively and the mean stand density was 1520 trees/ha. Overall, the most common defects observed on these trees were ramicorn

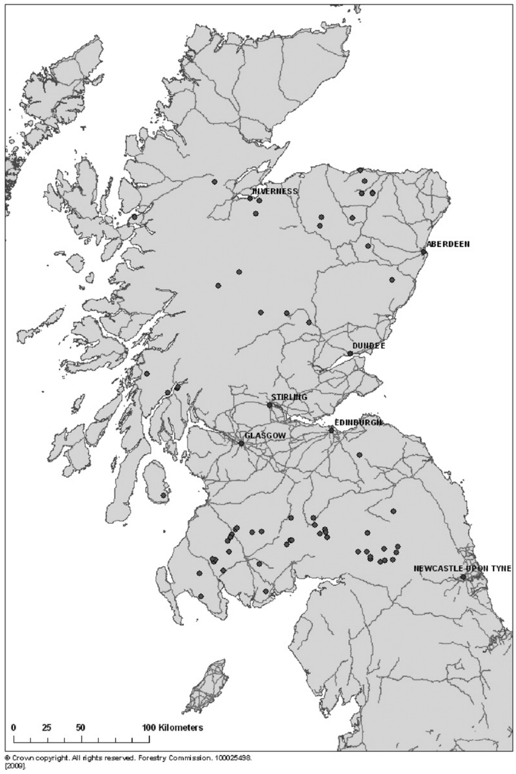

Fig. 1. Location of the 64 study sites across Scotland and northern England.

Table 3. Summary of the tree and stand-level attributes of the 64 sites sampled. Standard deviations of the attributes are given in parentheses after the mean.

Attribute	Level	Minimum	Maximum	Mean
DBH (mm)	Tree	76	555	230 (77)
Height (m)	Tree	10.9	37.3	22.1 (4.0)
Stress wave velocity (m/s)	Tree	1953	3506	2767 (208)
Dynamic MOE (kN/mm^2)	Tree	3.81	12.29	7.70 (1.15)
Age (years)	Stand	35	50	40 (3.7)
Stand density (trees/ha)	Stand	500	3000	1529 (518)
Live basal area (m^2/ha)	Stand	35.4	100.6	69.2 (14.9)
Dead basal area (m^2/ha)	Stand	0	21.5	4.9 (5.3)
Mortality [a)] (%)	Stand	0	56	22 (15)
Stem straightness	Stand	1.3	6.1	3.2 (1.1)
Stress wave velocity (m/s)	Stand	2469	3082	2775 (133)
Dynamic MOE (kN/mm^2)	Stand	6.09	9.50	7.72 (0.74)

[a)] Based on stand density

branches (37% of all live trees), stem scarring (9.2%) and sweep (6.3%) (Table 2). Approximately 6 per cent of the live trees were recorded as being unhealthy. This generally meant that they had a very small live crown and/or were carrying only one or two age classes of foliage. Trees described as unhealthy were often heavily suppressed and thus likely to succumb to competition-induced mortality. The incidence of multiple leaders and defective tops was relatively low with only 55 (2.8%) and 29 (1.5%) trees, respectively, having these defects.

3.2 Impact of Site and Stand Factors on Dynamic MOE

The stress wave velocity measurements were generally consistent between the north and south sides of the tree (Fig. 2), with a mean difference of 102 m/s. In the most extreme case, this difference was 711 m/s, possibly due to irregularities in stem shape, branching or the presence of compression wood on one side of the stem. The mean ratio of south-side to north-side velocity measurements was 0.99, but due to the large number of measurements and the relatively small standard error this ratio was significantly different from 1.00 ($p=0.01$). Predicted dynamic MOE of individual trees, based on the mean of the north and south side measurements, ranged from 3.81 kN/mm^2 up to 12.29 kN/mm^2. There was a very weak negative statistical relationship between dynamic MOE and DBH ($R^2=0.07$, $p<0.001$), however DBH only accounted for very small proportion of the observed variation in MOE. No significant difference in dynamic MOE was found between stem straightness classes (Fig. 3; $p=0.10$) with the straightest trees (class 7) having similar values of dynamic MOE as the least straight trees (class 1).

The variance components analysis showed that the majority (55 per cent) of the variation in dynamic MOE was due to differences between individual trees within a site. Approximately 35 per cent was due to differences between sites, and the remaining 10 per cent was due to differences between the north and south sides of the trees. At the site level, yield class and elevation both had a significant influence on dynamic MOE (Table 4). There was also a significant influence of the interactions between several of the factors on dynamic MOE. These interactions were elevation × latitude, latitude × spacing, elevation × latitude × longitude, and yield class × latitude × spacing (Table 4). There was suggestive but inconclusive evidence that initial spacing, yield class × longi-

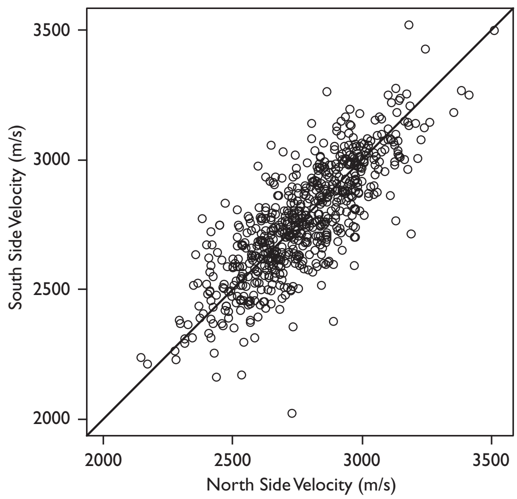

Fig. 2. Relationship between stress wave velocity measurements made on opposite sides of standing trees.

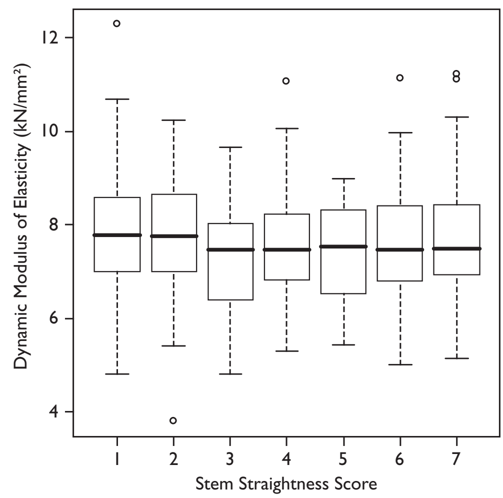

Fig. 3. Boxplot showing the range of dynamic MOE values for each stem straightness score.

Table 4. Summary of ANOVA for the effects of site and stand factors on stand-level dynamic MOE.

Factor	d.f.	Sum of squares	Mean square	F value	Pr(>F)	Significance [a)]
Yield class (YC)	1	2.3424	2.3424	6.9597	0.01277	*
Elevation (Elev)	1	3.6545	3.6545	10.8583	0.00241	**
Longitude (Long)	1	0.2691	0.2691	0.7995	0.37792	
Latitude (Lat)	1	0.1455	0.1455	0.4324	0.5155	
Initial spacing (Spacing)	1	1.2413	1.2413	3.6881	0.06375	.
Thinning (Thin)	1	0.2713	0.2713	0.8062	0.37596	
YC × Elev	1	0.5976	0.5976	1.7755	0.19211	
YC × East	1	1.2116	1.2116	3.5999	0.06684	.
Elev × East	1	0.6167	0.6167	1.8323	0.18534	
YC × Lat	1	0.2151	0.2151	0.6391	0.42993	
Elev × Lat	1	1.5317	1.5317	4.5512	0.04066	*
Long × Lat	1	0.341	0.341	1.0132	0.32169	
YC × Spacing	1	0.1461	0.1461	0.434	0.51473	
Elev × Spacing	1	0.4354	0.4354	1.2937	0.26381	
Long × Spacing	1	1.6648	1.6648	4.9465	0.03332	*
Lat × Spacing	1	0.0772	0.0772	0.2293	0.63533	
YC × Thin	1	0.6356	0.6356	1.8886	0.17891	
Elev × Thin	1	0.8407	0.8407	2.4979	0.12383	
Long × Thin	1	0.5821	0.5821	1.7296	0.19781	
Lat × Thin	1	0.1922	0.1922	0.5712	0.45533	
Spacing × Thin	1	0.7841	0.7841	2.3297	0.13675	
YC × Elev × Long	1	0.0687	0.0687	0.2042	0.65443	
YC × Elev × Lat	1	0.00001	0.00001	0.00004	0.99523	
YC × Long × Lat	1	0.1429	0.1429	0.4247	0.51924	
Elev × Long × Lat	1	1.7006	1.7006	5.0529	0.03161	*
YC × Elev × Spacing	1	1.1837	1.1837	3.5171	0.06989	.
YC × Long × Spacing	1	0.0786	0.0786	0.2336	0.63216	
Elev × Long × Spacing	1	0.4324	0.4324	1.2848	0.26543	
YC × Lat × Spacing	1	1.7064	1.7064	5.0702	0.03134	*
Elev × Lat × Spacing	1	0.6894	0.6894	2.0484	0.16206	
Long × Lat × Spacing	1	0.0117	0.0117	0.0349	0.85297	
Residuals	32	10.77	0.3366			

[a)] Significance levels are indicated by ** ($p<0.01$) and * ($p<0.05$). Suggestive but inconclusive evidence ($p<0.1$) is indicated by a ".".

tude and yield class × elevation × initial spacing had an influence on dynamic MOE.

A multiple regression model was developed based on the actual numerical values of the terms that were found to be significant in the ANOVA for the fractional factorial design. Age was also included in the model which had the following form:

$$Y_i = b_0 + b_1\text{Age} + b_2\text{YC} + b_3\text{Elev} + b_4\text{Lat} + b_5\text{IS} + b_6\text{Elev}\times\text{Lat} + b_7\text{YC}\times\text{Elev} + b_8\text{YC}\times\text{IS} + b_9\text{Elev}\times\text{IS} + b_{10}\text{YC}\times\text{Elev}\times\text{IS} + e_i$$

where Age is the stand age [years], YC is yield class [m^3/ha/year], Elev is the elevation [m], Lat is the latitude [m north from the Ordnance Survey datum], IS is the initial stand density [trees/ha] and $e_i \sim N(0,\sigma^2)$. Overall, the model was able to explain approximately 45 per cent of the site-to-site variation in predicted dynamic MOE. There was suggestive but inconclusive evidence of a positive relationship between dynamic MOE and stand age, while there were significant negative relationships with yield class, elevation and latitude ($p=0.032$, 0.003 and 0.015, respectively; Table 5). Interestingly, there was suggestive but inconclusive evidence of a negative relationship between dynamic MOE and initial stand density ($p=0.077$), however both two-way interaction terms containing initial stand density have

Table 5. Summary of the parameter estimates and their significance for the model to predict dynamic MOE.

Term	Parameter estimate	Standard error	t-value	Pr(>|t|)
Intercept	19.656	4.367	4.501	<0.0001
Age	5.173e-02	2.670e-02	1.937	0.05871
Yield class (YC)	–6.097e-01	2.773e-01	–2.199	0.03287
Elevation (Elev)	–5.071e-02	1.640e-02	–3.093	0.00333
Latitude (Lat)	–5.335e-03	2.116e-03	–2.522	0.01512
Initial spacing (IS)	–2.454e-03	1.358e-03	–1.807	0.07709
Elev × Lat	1.729e-05	7.741e-06	2.233	0.03034
YC × Elev	2.310e-03	1.073e-03	2.154	0.03644
YC × IS	1.536e-04	9.172e-05	1.674	0.10069
Elev × IS	1.089e-05	4.946e-06	2.202	0.03263
YC × Elev × IS	–6.935e-07	3.460e-07	–2.004	0.05084

positive coefficients. There was also significant positive relationship between dynamic MOE and the interaction between elevation and latitude ($p=0.036$). This may be due to a number of sites with low dynamic MOE that were found in the southwest of Scotland. There was no significant relationship between dynamic MOE and any of the climatic variables obtained from the Ecological Site Classification. There was some suggestion that the mean dynamic MOE was higher in warm dry and cool dry sites compared with cool wet and cool moist sites. However, due to the unbalanced nature of the data, it was not possible to undertake a formal comparison between climatic zones.

4 Discussion

This study has shown that there is considerable variation in dynamic MOE both within and between Sitka spruce stands growing in northern Britain. Because MOE is related to wood density and microfibril angle (Evans and Ilic 2002), the variation in MOE observed in this study is assumed to be due to variation in these two properties between trees and between sites. Differences between stands reflect differences in broad-scale environmental and management factors, while differences between individual trees within a stand are likely to be the result of the combination of genetic variation between trees as well as small scale site effects such as localised differences in soil properties and the available growing space. Given the age of the stands, they would have most likely been established using material grown from seed that was imported from the Queen Charlotte Islands of Canada (Fletcher 1992). Because this seed was collected from the general population of trees rather than from seed orchards, there was a large amount of inter-tree variation in the traits of the trees grown from it (Fletcher 1992). The large amount of tree-to-tree variation in wood stiffness indicates that there is an opportunity to improve this property through tree breeding. The current Sitka spruce tree breeding programme in the UK has focussed on increasing density, reducing branch size and improving stem straightness as the main means of improving wood quality (Lee 1999). Sitka spruce wood properties differ in the degree to which they are under genetic control (Rozenberg and Cahalan 1997), but to our knowledge no published data currently exist for the heritability of wood stiffness in this species. However, Hanrup et al. (2004) found that the narrow-sense heritability (h^2) of MOE in Norway spruce (*Picea abies* (L.) Karst.) was less than 0.2, while research conducted in open-pollinated radiata pine (*Pinus radiata* D. Don) found that the heritability of modulus of rupture and modulus of elasticity were 0.24 and 0.25, respectively (Kumar 2004). While this is lower than the heritability for density (e.g., 0.64 in the radiata pine study), increases in density are not always associated with increases in wood stiffness, particularly when microfibril angle is high (Walker 2006). With the increased planting of full-sib seedlings and vegetatively propagated cuttings, it is expected that the magnitude of this tree-to-tree variation in wood properties within a stand could decrease in the future (Thompson 1992).

The differences in dynamic MOE between sites were strongly and negatively related to elevation. A similar effect was observed for radiata pine trees growing in Tasmania (Cown et al. 2006). Elevation has also been found to be most important factor affecting the productivity of Sitka spruce plantations growing in northern Britain (Malcolm and Studholme 1972, Blyth and MacLeod 1981, Worrell and Malcolm 1990a, 1990b). This is because elevation is highly correlated with a number of climatic factors such as growing season temperature (accumulated temperature), rainfall and windiness which are known to affect tree growth (Grace 1977, Cannell and Smith 1983). Therefore, it is to be expected that yield class will be associated with elevation and latitude. While the experimental design enabled the influence of factors such as yield class, elevation and latitude on MOE to be examined individually, it is more difficult to separate their influences when attempting to determine the underlying mechanisms through which they actually affect MOE. For this reason, more detailed designed experiments are needed to better elucidate these causal mechanisms.

An example of such an experiment is presented in Watt et al. (2006) who found a strong positive relationship between mean annual temperature and the dynamic MOE of young radiata pine growing at a range of sites in New Zealand. In their study, meteorological measurements were made at each of the 21 sites investigated, and these sites in turn encompassed the complete range of latitude, mean annual rainfall and mean annual temperature values for the exotic plantations in that country. Accumulated temperature was not found to be significantly related to the dynamic MOE of Sitka spruce, despite the fact that it was negatively related to elevation at the 64 sites ($R^2 = 0.66$). In this study mean accumulated temperature was predicted for each 10 km grid square within the UK, however there is likely to be substantial finer scale variation within each grid cell. Therefore, the accumulated temperature at the actual measurement site itself could differ considerably from the average value determined from the Ecological Site Classification.

The absence of relationships between dynamic MOE and either accumulated temperature or moisture deficit may also be due to the relatively limited range of these variables across the sites sampled. This study focussed on northern Britain which contains the majority of Sitka spruce in the UK. However, smaller areas of Sitka spruce exist in more southerly latitudes in the UK (e.g., Exmoor) where the accumulated temperature is greater than 1900 day degrees and the moisture deficit is in excess of 140 mm (Pyatt et al. 2001). The absence of more southerly sites may also explain the lack of a relationship between MOE and latitude in the ANOVA where latitude was treated as a factor. When latitude was represented as a continuous variable in the multiple regression analysis, a significant negative relationship was found with MOE. This was not unexpected as latitude is known to affect wood density (e.g., Bryan and Pearson 1955), which in turn is a key determinant of wood stiffness (Evans and Ilic 2001). Temperature and photoperiod, both of which vary with latitude, affect the initiation and cessation of growth (Cannell and Smith 1983) and also the formation of high density and high stiffness latewood (Watt et al. 2005). While Bryan and Pearson (1955) only sampled six sites across the UK, these covered a latitudinal range of 6°34´ (50°48´N to 57°23´N), whereas the 64 sites investigated here covered a range of 3°01´(54°39´N to 57°40´N). It is recommended that a wider range of latitudes should be sampled in the future in order to provide a dataset which can be used to determine more conclusively what if any effects temperature, moisture deficit and latitude have on wood stiffness.

The negative relationship between MOE and growth rate as measured by yield class is consistent with studies which have shown that there is generally a negative relationship between growth rate and wood density (Saranpää 2003) and a positive relationship with microfibril angle (Saren et al. 2004). In Sitka spruce, Brazier (1967, 1970) found that there was a negative relationship between growth rate and wood density, due to the greater proportion of lower density earlywood in wider growth rings. While differences in growth rate often represent differences in genetic potential as well as in site characteristics, they can also be due to forest management practices. In particular, between 1972 and 1981 approximately 100 000 ha in south west Scotland (Dumfries and Galloway) were treated with remedial fertiliser programmes in which up to a total of 1725 kg/ha of P and K and 350 kg/ha of N were applied in the first 12 years (Davies 1982). Previous studies which have investigated the effects of fertilisation on wood properties of radiata pine have shown that this results in a small decrease in MOE (Downes et al. 2002, Watt et al. 2006). However, in the latter study the 6 per cent decrease was not statistically significant. More detailed investigation is required to determine the history of fertiliser application for each stand, provided that records exist, in order to determine whether these stands had higher rates of growth and lower dynamic MOE. Similarly, more information is needed on the timing and intensity of thinning operations conducted in each stand as at present thinning is only recorded as present or absent. In the UK many stands are managed on a no-thin regime due to the risk of wind damage (Cameron 2002). Where thinning is carried out, it is often systematic rather than selective or is done pre-commercially in order to improve stand stability (Cameron 2002). These different types of thinning regimes will vary in terms of their impacts on final log quality including wood properties. Early pre-commercial thinning generally results in an increased proportion of juvenile wood and larger branches, while later commercial thinning generally reduced the proportion of juvenile wood (Brazier and Mobbs 1993, Pape 1999). Pape (1999) also found that heavy commercial thinning in Norway spruce stands reduced basic density, while lighter more frequent thinning did not affect this property.

In addition to wood properties, stem form is also an important aspect of wood quality as this affects the proportion of total stem volume that is merchantable. Macdonald et al. (2009) found that there was a significant positive relationship between the mean stem straightness score for a stand and the proportion of highest grade sawlogs recovered. It was hypothesised that more crooked trees would contain higher amounts of compression wood, which in turn would have a lower MOE (Timell 1986). However, there was no relationship between stem straightness and dynamic MOE, although the sensitivity of stress wave velocity measurements to the presence of compression wood is unknown. From the results obtained here, it is apparent that there is a wide range of dynamic MOE values within and between stands containing trees with good stem form. Therefore, techniques such as stress wave velocity measurements could prove very valuable as a means for determining the suitability of a stand or individual trees within a stand to yield structural timber.

In conclusion, this study has shown that it is possible to predict a significant proportion of the site level variation in dynamic MOE from information that is generally held by commercial forestry enterprises in the UK. Therefore, it should be possible to develop maps showing the spatial variation in wood stiffness in 35–45-year-old stands across northern Britain. This information in combination with data on stem form could be linked to future wood supply forecasts in order to provide an estimate of the proportion of the future wood volume that is suitable for producing construction-grade timber. In order to verify the results obtained from measurements on standing trees, a sample of the 64 stands spanning the full range of values of dynamic MOE will be felled and the mechanical properties of the timber measured.

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