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ORIGINAL PAPER

Within- and between-stand variation in selected properties of Sitka spruce sawn timber in the UK: implications for segregation and grade recovery

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Abstract

- ***Context*** Information on wood properties variation is needed by forest growers and timber processors to best utilise the available forest resource and to guide future management.
- ***Aim*** This study aims to quantify the variation in selected properties of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) structural timber.
- ***Methods*** Twelve harvest-age stands were selected, ten trees per site were felled and processed into 301 logs. Dynamic modulus of elasticity ($\mathrm{MOE_{dyn}}$) was measured on each tree and log using portable acoustic instruments. Logs were processed into structural timber and its MOE and bending strength was determined.
- ***Results*** Overall, the timber satisfied the MOE, bending strength and density requirements for the C16 strength class. Approximately 25 % of the total variation in timber mechanical properties was attributed to between-stand differences, with the remaining 75 % attributed to within-stand differences. A series of equations were developed to predict site, tree and log-level variation in timber properties.
- ***Conclusion*** Knowledge of the site and stand factors that are associated with differences in timber properties can assist with segregation of the current resource. Portable acoustic tools can also be used to increase the stiffness of sawn timber by segregating out individual trees and logs that will yield low stiffness timber.

Keywords Acoustics · Timber properties · Structural timber · Modulus of elasticity · Wood quality · Segregation

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Contribution of Co-Authors John Moore initiated the study, undertook field and laboratory measurements, analysed the data and wrote the final paper. Andrew Lyon assisted with developing the methodology for the study, organised the fieldwork and timber processing in the sawmill, assisted with field and laboratory measurements and contributed to the final report. Gregory Searles and Stefan Lehneke assisted with the laboratory measurements and contributed to the final report. Daniel Ridley-Ellis assisted with the laboratory measurements, analysis of the data and contributed to the final report.

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1 Introduction

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the main conifer species grown in the UK. The total area of Sitka spruce plantations is approximately 730,000 ha (Forestry Commission 2010) and the commercial wood products industry in the UK is primarily based on this species. Wood from this tree is used in the production of paper and panel products, but the majority is sawn into timber for use in construction, pallets/packaging and fencing (McIntosh 1997). The domestic construction market is seen as a high priority for expansion due to its relative size and value. The three properties that are used to assign structural timber to a strength class under EN338 (CEN 2009a) are bending strength, bending stiffness and density. Bending stiffness is a key property of interest, as it is generally the property that limits the grade that UK-grown Sitka spruce can achieve (Moore 2011). In the UK, Sitka spruce is normally machine strength graded using a C16/reject setting. Currently, pass rates in excess of 90 % are obtained when timber is graded to C16, but 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 20–25 years will be lower than that of the current resource (McIntosh 1997; Macdonald et al. 2009). These concerns were mostly related to stem form, but there was also an appreciation of the effects that changes in forest management practices (in particular increased initial planting spacing) may have had on internal wood properties. Furthermore, there is likely to be substantial variation in the wood properties of the current Sitka spruce forest resource due to differences in site conditions, genetics and silvicultural practices. This, in turn, could mean that yields of structural grade timber could also vary between sites as well as between trees within a site.

In order for the local wood processing sector to better utilise the Sitka spruce forest resource and to plan future investment, they require information on the extent and sources of variation in wood properties, as well as practical methods for segregating raw material on the basis of these properties. Historically, the segregation of trees and logs has been made on the basis of external characteristics, such as branch size, straightness and diameter (Forestry Commission 1993). While this generally provides valuable information on the volume and appearance of timber that can be recovered, it is not necessarily a good predictor of the mechanical properties of this timber (Riddout et al. 1999; Wagner et al. 2003). However, in recent years the use of acoustic (or stress wave)-based instruments for segregating material based on wood properties, particularly modulus of elasticity, has become more common (e.g. Wang et al. 2007). In particular, there has been increased use of time-of-flight and resonance-based tools by the forestry sector in countries such as New Zealand (e.g. Walker and Nakada 1999; Tseheye et al. 2000; Carter et al. 2006), Australia (Dickson et al. 2004) and the USA (e.g. Wang et al. 2000, 2001, 2002, 2004b).

In 2006/2007, a study commenced to investigate the effects of various site and silvicultural factors on the physical and mechanical wood properties of Sitka spruce growing in the UK, and to determine whether these properties could be predicted from measurements made on trees and logs using portable acoustic tools. The initial assessment of wood properties was based on measurements made on standing trees using a portable stress wave timer (IML Hammer, Instrumenta Mechanic Labor GmbH, Germany) at a total of 64 harvest-age stands (i.e. 35–45 years old) located throughout Scotland and northern England (Moore et al. 2009b). At each site, ten trees were measured and the predicted dynamic modulus of elasticity ($\mathrm{MOE}_{\mathrm{dyn,tree}}$) of the 640 trees that were assessed ranged from 3.81 to 12.29 kN mm^{-2}, while the site mean values ranged from 6.09 up to 9.74 kNmm^{-2}. Approximately, 36 % of the variation in $\mathrm{MOE}_{\mathrm{dyn,tree}}$ was due to differences between sites, with 55 % due to differences between trees within a site. The remaining variation was due to differences between the two sets of measurements made on opposite sides of the tree. Variation in $\mathrm{MOE}_{\mathrm{dyn,tree}}$ at the site level was significantly associated with yield class (a measure of site productivity based on the maximum mean annual increment of stand volume), elevation, latitude, longitude and initial spacing as well as with a number of interactions between these factors. A multiple regression model incorporating these variables was able to explain 45 % of the site-level variation in $\mathrm{MOE}_{\mathrm{dyn,tree}}$. In order to determine whether these observed differences between sites translate into differences in the mechanical properties and subsequent grade recovery of sawn timber, a processing study was undertaken in which trees from contrasting sites were felled and the properties of the sawn timber were compared.

This paper presents the results from a study to validate the use of stand and tree-level measurements (e.g. acoustic velocity, crown ratio) to predict sawn timber properties. Trees from 12 sites, with mean values of $\mathrm{MOE}_{\mathrm{dyn,tree}}$ that span the full range of site–mean values observed for the original 64 sites from the study by Moore et al. (2009b), were processed into timber, machine strength graded and mechanically tested. These data are used to quantify the extent of within- and between-stand variation in timber mechanical properties to understand some of the drivers of this variation and to investigate the relationship between timber mechanical properties and measurements made on trees and logs using portable acoustic tools.

2 Methods

2.1 Site selection and field measurements

The 12 sites chosen for the processing study were selected from the original 64 sites sampled by Moore et al. (2009b) using stratified random sampling. The three strata were based on site mean values of $\mathrm{MOE}_{\mathrm{dyn,tree}}$. Four sites had a mean value of $\mathrm{MOE}_{\mathrm{dyn,tree}}$ greater than 9 kNmm^{-2}, four had a value less than 7 kNmm^{-2} and the remaining four had values between 7 and 9 kNmm^{-2}. These values corresponded to the upper and lower quartiles of the distribution of $\mathrm{MOE}_{\mathrm{dyn,tree}}$. The characteristics of the 12 sites selected are given in Table 1. At each site, the original ten trees that had been measured in the earlier study were located. In most cases, one or more of these trees had to be replaced with another tree in the plot due to the inability to obtain a single sawlog of merchantable size or quality from them; a total of 29 replacements were made and these replacement trees had their stress wave velocity measured with the IML hammer. Each selected tree was felled and its

Table 1 Characteristics of the 12 sites selected for felling

Site ID	MOE class[a]	Ownership	OS grid	Elevation (m)	Slope (deg)	Median stem straightness score	Mean DBH (mm)
339	<7	Public	NJ532100	356	3	2	241
285	<7	Public	NM896158	220	23	2	263
23	<7	Private	NX512953	344	9	2	255
5313	<7	Public	NN740613	357	0	2	311
449	7–9	Private	NG819324	96	19	2	214
2946	7–9	Public	NH729441	203	0	4	285
2792	7–9	Public	NH699346	269	4	4	228
412	7–9	Private	NJ170254	401	8	3	245
5544	>9	Public	NN929610	438	0	3	193
157	>9	Private	NS963095	314	9	1	273
250	>9	Private	NX728756	212	10	2	201
85	>9	Private	NX389769	141	5	1	246

[a] Based on standing tree measurements made using the IML Hammer by Moore et al. (2009b)

total height, height to lowest live branch and height to lowest live whorl (i.e. the whorl with live branches in three of four quadrants) were measured. The diameter at breast height (DBH) and heights of felled trees ranged from 193 up to 453 mm and from 16.7 up to 31.6 m, respectively. Up to three 3-m-long sawlogs were cut from each tree starting at breast height (1.3 m). This starting height was selected as a breast height disc and a 0.5-m-long log from immediately below breast height were taken from each tree for measurement of other wood properties. The breast height age of each tree was determined from ring counts made on the breast height discs. The dimensions of all logs were recorded and a longitudinal stress wave velocity measurement was made on each of them using the HM-200 tool (Fibre-gen, Auckland, New Zealand). The dynamic modulus of elasticity ($MOE_{dyn,log}$ [in kilonewton per square millimeter]) was calculated for each log from stress wave velocity (V [in kilometer per second]) and bulk density (ρ_{bulk} [in kilogram per cubic meter]) using the following equation:

$$MOE_{dyn,log} = \rho_{bulk} V^2 \tag{1}$$

The bulk density of each log was assumed to be 1,000 kg m^{-3}. While Searles (2012) suggested that predictions of $MOE_{dyn,log}$ could be improved by measuring ρ_{bulk}, this was not done in this study due to the high cost of making these measurements and the low likelihood that it would be done operationally in the forest. Logs were then marked with a unique paint colour and stamp combination so that they could be linked to the tree and site they were cut from. A total of 301 logs were cut from the across the 12 sites, with most sites yielding at least 25 logs (Table 2). In most cases, stands were in the target age range of 35–45 years; however, site 449 only had a breast height age of 26 years. This sample plot had been relocated by approximately 100 m during the earlier study by Moore et al. (2009b) as part of the stand at the intended location for this plot had been felled.

The logs were then transported to either BSW Timber's Boat of Garten sawmill or Adam Wilson and Sons' sawmill at Troon, Scotland, where they were sawn using a standard cutting pattern that maximised the yield of 47×100 mm timber. A total of 959 pieces of structural timber with these dimensions were cut and each piece was uniquely numbered so that it could be linked to the site, tree and log that it came from (unfortunately the numbers were damaged on four pieces of timber and could not be read). This timber was then kiln dried to 18 % moisture content and machine strength graded with a GoldenEye-702 X-ray grader (MiCROTEC, Italy) using the model given in TG1/1005/08 (CEN 2009b). The value of the indicating property (IP) determined by the grading machine was recorded for each piece of timber and there was no visual override by the machine operator.

2.2 Laboratory measurements

Prior to testing, the timber was stored in a controlled environment (20 °C and 65 % relative humidity) at Edinburgh Napier University until it reached constant mass. Four-point bending tests were conducted on each piece of timber using a Zwick Z050 universal testing machine (Zwick Roell, Germany). Tests were performed in accordance with the procedures described in EN 408:2003 (CEN 2003) and EN384:2010 (CEN 2010a). Global modulus of elasticity (MOE_G) and modulus of rupture were calculated from the data obtained during these tests using the equations given in EN 408 (CEN 2003). Local modulus of elasticity (MOE_L) was also measured simultaneously on timber from three of the sites (329 pieces of timber in total) in order to examine the relationship between MOE_L and MOE_G. Following testing, a nominally 40-mm thick density sample spanning the

Table 2 Characteristics of the logs and trees sampled from the 12 selected sites. Standard errors are given in parentheses

Site ID	BH age (years)	Height (m)	DBH (mm)	Live crown ratio[a]	Number of logs [number of boards]				$MOE_{dyn,log}$ ($kN\ mm^{-2}$)				
					Log 1	Log 2	Log 3	Total	Tree	Log 1	Log 2	Log 3	All logs
339	33	18.4 (0.8)	259 (37)	0.59 (0.10)	10 [26]	9 [18]	4 [8]	23 [52]	6.76 (1.14)	10.32 (1.20)	9.06 (1.20)	8.20 (0.84)	9.36 (1.39)
285	38	20.8 (2.2)	278 (54)	0.36 (0.07)	10 [49]	10 [43]	7 [29]	27 [121]	6.69 (0.63)	11.71 (1.37)	11.81 (1.05)	11.49 (1.31)	11.67 (1.21)
23	36	24.4 (0.9)	261 (33)	0.38 (0.03)	10 [36]	8 [22]	1 [2]	19 [60]	6.87 (0.66)	10.53 (1.33)	10.28 (1.51)	11.14 (0.78)	10.51 (1.33)
5313	38	19.6 (2.6)	251 (69)	0.46 (0.09)	10 [59]	9 [48]	8 [40]	27 [147]	6.92 (0.65)	11.25 (1.10)	11.03 (0.99)	10.44 (0.99)	10.94 (1.05)
449	26	27.8 (2.2)	297 (44)	0.48 (0.08)	10 [28]	9 [21]	6 [16]	25 [65]	6.61 (0.61)	10.63 (1.39)	10.08 (1.95)	9.13 (0.95)	10.00 (1.58)
2946	37	22.5 (1.4)	299 (52)	0.45 (0.06)	10 [34]	9 [26]	8 [20]	27 [80]	7.90 (0.59)	12.51 (0.83)	12.02 (0.94)	11.25 (0.57)	11.97 (0.93)
2792	33	18.4 (1.4)	259 (27)	0.47 (0.07)	10 [32]	8 [19]	5 [10]	23 [61]	7.52 (0.71)	11.80 (1.32)	11.87 (1.37)	11.14 (0.96)	11.66 (1.25)
412	40	21.8 (1.4)	254 (46)	0.52(0.07)	8 [20]	9 [18]	6 [14]	23 [52]	7.61 (0.76)	12.24 (1.15)	11.31 (0.97)	9.89 (0.73)	11.24 (1.34)
5544	36	22.0 (1.1)	262 (27)	0.36 (0.04)	10 [22]	10 [20]	5 [9]	25 [51]	8.81 (1.39)	12.25 (1.21)	11.50 (1.15)	10.27 (1.04)	11.55 (1.33)
157	47	25.9 (2.6)	316 (67)	0.29 (0.06)	9 [46]	9 [45]	8 [34]	26 [125]	8.82 (1.08)	13.46 (1.16)	13.83 (1.54)	13.10 (1.64)	13.48 (1.43)
250	35	21.7 (1.6)	235 (38)	0.37 (0.06)	9 [31]	9 [28]	9 [22]	27 [81]	8.50 (0.69)	13.07 (1.80)	12.67 (1.78)	12.32 (1.44)	12.70 (1.66)
85	36	19.8 (1.6)	244 (27)	0.31 (0.06)	10 [28]	9 [21]	5 [11]	24 [60]	9.38 (0.89)	14.03 (1.11)	13.86 (1.40)	13.08 (1.63)	13.69 (1.38)
Overall		22.7 (3.5)	272 (51)	0.42 (0.11)	116 [411]	108 [329]	72 [215]	296 [955]	7.70 (1.24)	11.98 (1.66)	11.62 (1.87)	11.07 (1.82)	11.61 (1.81)

[a] Ratio of live crown length to total tree height

full cross-section was cut from each specimen. These samples were weighed immediately and their volume determined from dimensional measurements. Samples were then dried in an oven at 103 °C for 72 h and moisture content calculated from gravimetric measurements in accordance with EN 13183-1 (CEN 2002). Wood density at ambient moisture content was calculated from measurements of sample mass and volume in accordance with ISO 3131 (ISO 1975). In addition, the average ring width was determined for these samples using the method described in EN1310 (CEN 1997).

2.3 Data analysis

Data were analysed using the R open source statistical package (R Development Core Team 2012). Values of MOE_L, MOE_G and bulk density were adjusted to a 12 % moisture content basis, while values of bending strength were adjusted to a 150 mm nominal depth following the procedures described in EN384:2010 (CEN 2010a). A linear model was fitted to the measurements of $MOE_{L,12}$ and $MOE_{G,12}$ (i.e. MOE_L and MOE_G adjusted to 12 % moisture content) made on 329 pieces of timber. This equation was then used to predict an equivalent pure bending modulus of elasticity (MOE_{PB}) from $MOE_{G,12}$ for all 955 pieces of timber. Linear regression was used to investigate the relationships between modulus of rupture, modulus of elasticity and density. The following random-effects model was then used to estimate the between- and within-stand variation in density, MOE_{PB} and MOR. In this analysis, a nested structure was assumed for the random effects of log, tree and site in accordance with the experimental design:

$$y_{ijkl} = \mu + S_i + T_{j(i)} + L_{k(ij)} + e_{l(ijk)} \qquad (2)$$

where y_{ijkl} is the measurement of density, MOE_{PB} or MOR on an individual specimen, μ is the overall mean, S_i is the random effect of the *i*th site ($\sim N(0, \sigma_S^2)$), $T_{j(i)}$ is the random effect of the *j*th tree within the *i*th site($\sim N(0, \sigma_T^2)$), $L_{k(ij)}$ is the random effect of the *k*th log within the *j*th tree($\sim N(0, \sigma_L^2)$), and $e_{l(ijk)}$ is the random effect of the *l*th piece of timber from the *k*th log ($\sim N(0, \sigma_e^2)$).

Pairwise correlations were determined between stand-level average values of IP value, MOE_{PB}, MOR, timber density (DENS), $MOE_{dyn,log}$ and $MOE_{dyn,tree}$, elevation (ELEV [in meter]), latitude (LAT [in kilometers north from the Ordinance Survey datum]), basal area (BA [in square meter per hectare]), stand density (SD [trees per hectare]), breast height age (BHage [in years]), DBH (in millimeter), total height of the tree (*H* [in meter]), height to diameter ratio (HD) and live crown ratio (LCR, ratio of live crown length to total height). Multiple linear regression analysis was used to determine which combination of these variables could explain differences in stand-level values of $\mathrm{MOE}_{\mathrm{dyn,log}}$, IP value, $\mathrm{MOE}_{\mathrm{PB}}$, MOR and timber density. For individual logs, a linear mixed-effects model (Pinheiro and Bates 2000) was used to examine potential relationships between both $\mathrm{MOE}_{\mathrm{dyn,log}}$ and the average $\mathrm{MOE}_{\mathrm{PB}}$ of timber cut from logs and different site, tree and log variables. In addition to the variables already described, small-end log diameter (SED [in millimeter]), large-end diameter (LED [in millimeter]) and log position (POS, i.e. 1, 2 or 3 depending on whether it is the bottom, middle or top log) were also included in the analysis. The models included random effects for site ($\sim N(0, \sigma_S^2)$) and tree within site ($\sim N(0, \sigma_T^2)$). Similar models were also developed for $\mathrm{MOE}_{\mathrm{PB}}$ of individual boards. The average growth ring width (RW [in millimeter]) measured on each board was included as a fixed effect in the model along with a random effect for log within tree ($\sim N(0, \sigma_L^2)$).

The characteristic values of modulus of elasticity, bending strength and density for each site were calculated using the procedures described in EN384 (CEN 2010a). The characteristic values for modulus of elasticity were equal to the mean value of $\mathrm{MOE}_{\mathrm{PB}}$, while characteristic values for density and bending strength were calculated from the fifth percentile values of density and MOR (adjusted to a 150 mm timber depth). In accordance with EN384, the fifth percentile values of MOR were multiplied by 0.8 on the basis that only a single sample containing between 52 and 147 pieces of timber was taken from each site (i.e. k_s=0.8). Because the timber had been machine strength graded, the fifth 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 characteristic values, timber was assigned to a strength class based on the requirements given in EN338 (CEN 2009a). 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 % of the required value for that strength class. The differences in these characteristic values and the resulting strength class between sites were compared and linear regression analysis used to investigate potential relationships with stress wave velocity measurements made on standing trees and felled logs. The utility of portable acoustic tools to improve the grade out-turn of sawn timber was examined by setting various stress wave velocity thresholds for trees and logs, and calculating the characteristic values for bending strength, stiffness and density of the timber sawn from those trees and logs which had a velocity greater than this threshold value. In this analysis, sites in the 7–9 kN mm^{-2} MOE class (i.e. 412, 449, 2,792 and 2,946) were given a double weighting as these represent the interquartile range of harvest-age sites based on earlier standing tree measurements (Moore et al. 2009b). Without this additional weighting, these stands would only represent one third of the sample analysed in this study, whereas in fact they represent approximately half the mature Sitka spruce stands in the wider population.

The potential yields of different strength classes of timber were determined by calculating the optimum grade that each piece of timber could be assigned to following the approach presented in EN 14081-2 (CEN 2010b). This analysis was performed for each individual site and for the resource as a whole. In the latter analysis, boards from those sites in the 7–9 kN mm^{-2} MOE class were given a double weighting. The optimum yields were determined for all strength classes from C16 up to C27 as well as TR26 (a grade, used in the UK, for trussed rafters). For each strength class of interest, pieces of timber were ranked according to their value of $\mathrm{MOE}_{\mathrm{PB}}$ and assigned to the optimum grade. Characteristic values of bending strength ($f_{\mathrm{m,k}}$), modulus of elasticity ($E_{0,\mathrm{mean}}$) and density (ρ_k) were calculated for each grade according to EN 384, and checks were made to verify that these characteristic values satisfied the requirements for each grade.

3 Results

3.1 Tree and log measurements

The mean value of $\mathrm{MOE}_{\mathrm{dyn,log}}$ at each site ranged from 9.36 up to 13.69 kN mm^{-2} and was significantly correlated with the site-level mean values of $\mathrm{MOE}_{\mathrm{dyn,tree}}$ (ρ=0.844), latitude (ρ=−0.588), breast height age (ρ=0.569) and live crown ratio (ρ=−0.794; Table 3). Aside from $\mathrm{MOE}_{\mathrm{dyn,tree}}$, the strongest of these correlations was with live crown ratio; stands containing trees with deep crowns had a lower mean value of $\mathrm{MOE}_{\mathrm{dyn,log}}$ than those stands with shorter crowns. When live crown ratio was included in the model to predict mean value of $\mathrm{MOE}_{\mathrm{dyn,log}}$ at a site, no other site or stand-level variables were significant. If LCR was excluded from the model, $\mathrm{MOE}_{\mathrm{dyn,log}}$ was significantly related to elevation, DBH and breast height age (Table 4). For individual logs, the value of $\mathrm{MOE}_{\mathrm{dyn,log}}$ decreased with increasing position up the stem and the mean value was approximately 0.91 kN mm^{-2} lower for logs cut from position 3 (7.3–10.3 m above the base of the tree) than for butt logs (Table 2). $\mathrm{MOE}_{\mathrm{dyn,log}}$ of individual logs was significantly related to elevation, breast height age, large end diameter, and tree height to diameter ratio. The two different equations that were developed were each able to explain approximately 44 % of the variation in $\mathrm{MOE}_{\mathrm{dyn,log}}$ (Table 4).

3.2 Mechanical properties of sawn timber

Of the 959 boards that were machine strength graded, 937 (97.7 %) exceeded the threshold IP value for C16 strength class. There was considerable variation in strength grading

Table 3 Pairwise correlations (ρ) at a site level between timber properties and selected stand and site characteristics. Correlations are based on site-level means for each of the 12 sites

Log or timber property	Site characteristics or stand-level mean values of selected tree and log characteristics										
	$\mathrm{MOE}_{\mathrm{dyn,log}}$	$\mathrm{MOE}_{\mathrm{dyn,tree}}$	ELEV	LAT	BHage	DBH	HT	LCR	HD	BA	SD
$\mathrm{MOE}_{\mathrm{dyn,log}}$	–	0.844*	−0.253	−0.588**	0.569**	0.060	0.376	−0.794***	0.472	0.365	0.187
IP value	0.721*	0.833*	−0.181	0.435	0.115	−0.466	−0.174	−0.481	0.213	0.025	0.305
$\mathrm{MOE}_{\mathrm{PB}}$	0.897*	0.911*	−0.318	−0.534	0.266	−0.326	0.030	−0.626**	0.356	0.156	0.271
MOR	0.827*	0.900*	−0.317	−0.455	0.209	−0.400	0.043	−0.579**	0.457	0.168	0.356
ρ_k	0.556	0.630	−0.223	−0.454	−0.009	−0.487	−0.395	−0.346	−0.126	0.032	0.189

$^*p<0.001$, $^{**}p<0.05$, $^{***}p<0.01$, significance of the correlations

reject rates between sites; the best sites had 0 % rejects while the poorest site had 9.6 % rejects (excluding any pieces that would have been subsequently rejected on the basis of visual characteristics); however, there was no significant relationship between reject rate and either $\mathrm{MOE}_{\mathrm{dyn,tree}}$ or $\mathrm{MOE}_{\mathrm{dyn,log}}$ (p=0.40 and p=0.22, respectively). The mean IP value for each stand ranged from 6.59 up to 8.04 kN mm^{-2} and there were moderate correlations between the site mean IP value and the mean value of either $\mathrm{MOE}_{\mathrm{dyn,tree}}$ or $\mathrm{MOE}_{\mathrm{dyn,log}}$ (ρ=0.833 and ρ=0.721, respectively). The strength of this correlation was reduced by site 157, which despite being selected in the group of four sites with high values of $\mathrm{MOE}_{\mathrm{dyn,tree}}$, had a mean IP value for sawn timber (6.95 kN mm^{-2}) that was well below the expected value for such a stand (Fig. 1). The mean IP value for each stand was also significantly related to elevation, DBH and breast height age of the stand (Eq. (8), Table 4).

For the 955 pieces tested in the laboratory, values of $\mathrm{MOE}_{\mathrm{PB}}$ ranged from 3.47 up to 14.68 kN mm^{-2}, with a mean of 8.30 kN mm^{-2} (Table 5). $\mathrm{MOE}_{\mathrm{PB}}$ was only weakly related to density (R^2=0.29). Of the overall variation in $\mathrm{MOE}_{\mathrm{PB}}$, 26.3 % was attributed to differences between

Table 4 Equations for predicting log and timber properties at the stand, log and board level

Equation number	Equation form and parameter estimates	R^2	RMSE
	Stand-level equations (n=12)		
3	$\mathrm{MOE}_{\mathrm{dyn,log}} = 2.883 - 1.128\mathrm{MOE}_{\mathrm{dyn,tree}}$	0.71	0.731
4	$\mathrm{MOE}_{\mathrm{dyn,log}} = 16.444 - 11.626\mathrm{LRC}$	0.63	0.829
5	$\mathrm{MOE}_{\mathrm{dyn,log}} = 9.959 - 0.010\mathrm{ELEV} - 0.026\mathrm{DBH} + 0.310\mathrm{Hage}$	0.84	0.623
6	$\mathrm{IP} = 4.137 + 0.262\mathrm{MOE}_{\mathrm{dyn,log}}$	0.51	0.344
7	$\mathrm{IP} = 4.050 + 0.405\mathrm{MOE}_{\mathrm{dyn,tree}}$	0.69	0.274
8	$\mathrm{IP} = 9.260 - 0.002\mathrm{ELEV} - 0.015\mathrm{DBH} + 0.073\mathrm{BHage}$	0.58	0.359
9	$\mathrm{MOE}_{\mathrm{PE}} = -0.524 + 0.768\mathrm{MOE}_{\mathrm{dyn,log}}$	0.80	0.517
10	$\mathrm{MOE}_{\mathrm{PB}} = 0.334 + 1.042\mathrm{MOE}_{\mathrm{dyn,tree}}$	0.83	0.482
11	$\mathrm{MOE}_{\mathrm{PB}} = 11.802 - 0.008\mathrm{ELEV} - 0.035\mathrm{DBH} + 0.231\mathrm{BHage}$	0.84	0.589
12	$\mathrm{MOR} = 1.972 + 2.678\mathrm{MOE}_{\mathrm{dyn,log}}$	0.68	2.480
13	$\mathrm{MOR} = 2.986 + 3.890\mathrm{MOE}_{\mathrm{dyn,tree}}$	0.81	1.927
14	$\mathrm{MOR} = 49.332 - 0.031\mathrm{ELEV} - 0.141\mathrm{DBH} + 0.842\mathrm{BHage}$	0.81	2.158
15	$\mathrm{DENS} = 277 + 14.74\mathrm{MOE}_{\mathrm{dyn,tree}}$	0.39	18.4
	Log-level equations (n=296)		
16	$\mathrm{MOE}_{\mathrm{dyn,log}} = 7.737 - 0.008\mathrm{ELEV} + 0.252\mathrm{BHage} - 0.008\mathrm{LED} + \begin{cases} -0.589\,\mathrm{POS} = \mathrm{POS2} \\ -1.602\,\mathrm{POS} = \mathrm{POS3} \end{cases}$	0.43	0.591
17	$\mathrm{MOE}_{\mathrm{dyn,log}} = 3.052 - 0.007\mathrm{ELEV} + 0.192\mathrm{BHage} - 0.04\mathrm{HDR} + \begin{cases} -0.384\,\mathrm{POS} = \mathrm{POS2} \\ -1.148\,\mathrm{POS} = \mathrm{POS3} \end{cases}$	0.44	0.609
18	$\mathrm{MOE}_{\mathrm{PB}} = 1.255 + 0.616\mathrm{MOE}_{\mathrm{dyn,log}}$	0.45	1.262
	Board-level equations (n=955)		
19	$\mathrm{MOE}_{\mathrm{PB}} = 16.638 - 0.004\mathrm{ELEV} - 5.161\mathrm{LCR} - 0.004\mathrm{LED} - 0.737\mathrm{RW} + \begin{cases} 0.383\,\mathrm{POS} = \mathrm{POS2} \\ 0.777\,\mathrm{POS} = \mathrm{POS3} \end{cases}$	0.45	1.374
20	$\mathrm{MOE}_{\mathrm{PB}} = 5.409 + 0.498\mathrm{MOE}_{\mathrm{dyn,log}} - 0.510\mathrm{RW}$	0.47	1.344
21	$\mathrm{MOE}_{\mathrm{PB}} = 6.776 + 0.620\mathrm{MOE}_{\mathrm{dyn,tree}} - 0.626\mathrm{RW} + \begin{cases} 0.458\,\mathrm{POS} = \mathrm{POS2} \\ 0.851\,\mathrm{POS} = \mathrm{POS3} \end{cases}$	0.49	1.322

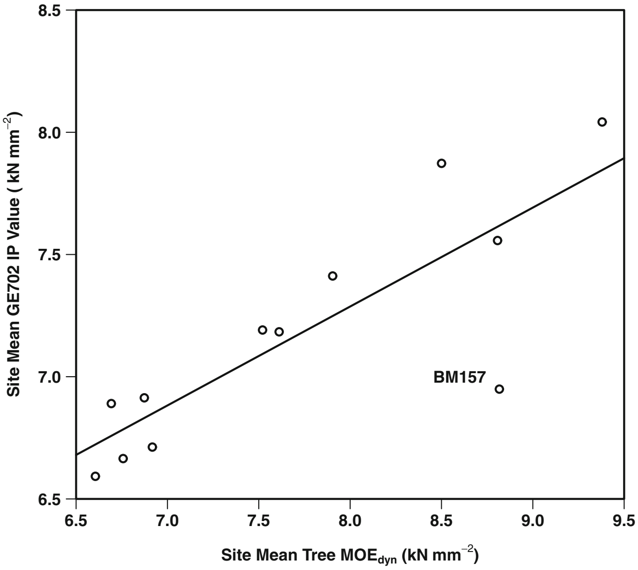

Fig. 1 Relationship between site-level values of dynamic modulus of elasticity calculated from measurements made on standing trees and the IP value of sawn timber measured by the GoldenEye-702 grading machine. The *solid line* was fitted using ordinary least squares regression

Table 6 Percentage of total variation in MOE$_{PB}$, density and MOR values attributable to each stratum in the experiment

Stratum	MOE$_{PB}$	Density	MOR
Site	26.3	22.7	18.3
Tree within site	36.2	51.1	25.2
Log within tree	2.2	1.4	4.5
Within log	35.3	24.9	51.9

stands, with the remaining 63.8 % attributed to within-stand differences—36.2 % to differences between trees within a stand and 35.3 % to differences between boards within a log (Table 6). Values of MOR ranged from 4.67 up to 58.54 N mm^{-2} and were moderately related to MOE$_{PB}$ (R^2=0.59), but only weakly related to wood density (R^2=0.19). Of the variation in MOR, 18.3 % was attributed to differences between stands, with 51.9 % of the total variation in MOR attributed to differences between boards within a log and 25.2 % attributed to differences between trees within a stand. Conversely, 51.1 % of the total variation in timber density was attributed to differences between trees within a stand, 24.9 % to differences between boards within a log and a further 22.7 % attributed to differences between stands. For all three properties, less than 5 % of the variation was attributable to differences between logs within a tree.

At a site level, there was a strong correlation between the mean value of MOE$_{PB}$ and both MOE$_{dyn,tree}$ and MOE$_{dyn,log}$ (ρ=0.90 and ρ=0.91, respectively; Fig. 2). There was also a significant negative correlation between the mean value of MOE$_{PB}$ at a site and live crown ratio (ρ=−0.63). Similar, but slightly weaker correlations were observed between these variables and MOR (Table 3). There was no significant correlation between density and any of the stand-level factors measured. Predictive equations involving MOE$_{dyn,log}$ and various site and stand factors were able to explain at least 80 % of the variation in MOE$_{PB}$ (Eqs. (9–11); Table 4). Similar equations were able to explain between 68 and 81 % of the variation in MOR (Eqs. (12–14); Table 4).

Table 5 Comparison of the properties of timber from different sites. The characteristic values for stiffness, bending strength and density are given by $E_{0,\mathrm{mean}}$, $f_{m,k}$ and ρ_k, respectively. The requirements for the strength classes are given in EN338 (the factor k_v=1.12 was applied to the requirement for bending strength)

Site	Wood property						
	Ring width (mm)	MOR (Nmm^{-2})	Density (kgm^{-3})	$E_{0,\mathrm{mean}}$ (kN mm^{-2})	$f_{m,k}$ (Nmm^{-2})	ρ_k (kgm^{-3})	Strength class
339	6.3	27.8	391	6.91	15.9	306	C14
285	6.0	30.9	384	7.68	17.7	332	C16
23	5.4	27.7	386	7.36	15.4	336	C14
5313	5.7	28.3	367	7.19	18.3	326	C14
449	7.0	31.3	355	7.45	20.6	302	C14
2946	5.7	33.2	392	8.57	23.0	344	C18
2792	5.3	31.5	404	8.56	16.6	353	C18
412	5.4	34.0	377	8.32	20.6	324	C16
5544	5.3	35.5	393	8.66	23.3	360	C18
157	5.1	35.3	373	9.12	22.5	331	C20
250	5.7	38.4	412	9.94	22.2	365	C22
85	5.4	41.2	441	10.51	25.0	354	C24
Overall	5.7	32.7	387	8.30	19.6	330	C16

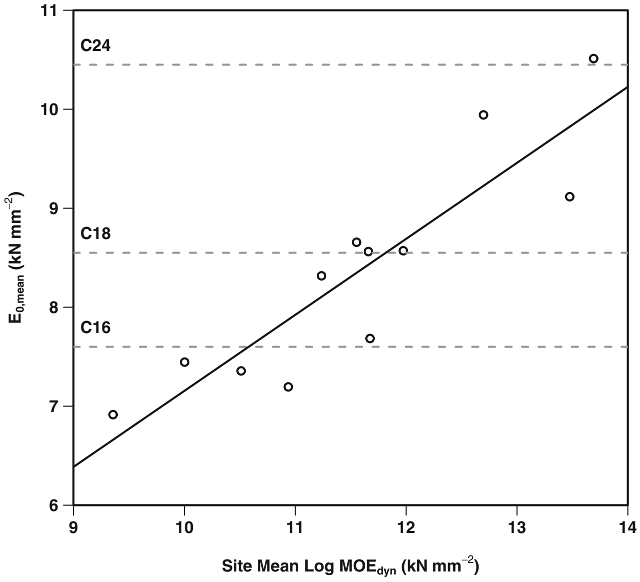

Fig. 2 Relationship between the mean log acoustic velocity at a site and the mean bending stiffness of timber cut from a site. The *solid line* was fitted using ordinary least squares regression, while the *horizontal grey lines* represent the threshold values of bending stiffness for the C16, C18 and C24 strength classes

Approximately 39 % of the variation in the mean timber density could be explained by MOE$_{\mathrm{dyn,tree}}$ (Eq. (15)); no other significant relationships could be developed to predict timber density. At a log level, there was a moderate relationship between the average MOE of boards cut from log and the value of MOE$_{\mathrm{dyn,log}}$ (R^2=0.45), while the relationship was slightly weaker for MOR (R^2=0.32). At an individual board level, approximately 47 % of the variation in MOE$_{\mathrm{PB}}$ could be explained by MOE$_{\mathrm{dyn,log}}$ and the average ring width of the board (Eq. (20); Table 4). A similar proportion of the variation could be explained using ELEV, LCR, LED, log position and RW (Eq. (19); Table 4). In contrast to the result for MOE$_{\mathrm{dyn,log}}$, the mean value of MOE$_{\mathrm{PB}}$ for timber cut from a log was higher in upper logs after accounting for all the other factors. Almost 50 % of the variation in MOE$_{\mathrm{PB}}$ of individual boards could be predicted from MOE$_{\mathrm{dyn,tree}}$, average ring width and log position (Eq. (21); Table 4). Again, for a given average ring width and value of MOE$_{\mathrm{dyn,tree}}$, MOE$_{\mathrm{PB}}$ was higher in boards cut from the upper two logs compared with boards cut from the butt log.

3.3 Assignment to strength classes and optimal grading

Overall, the timber had characteristic values of density (ρ_k), bending strength ($f_{m,k}$) and MOE ($E_{0,\mathrm{mean}}$) that were sufficient for it to achieve the requirements for the C16 strength class (Table 5). However, there were considerable differences in the characteristic values of these properties between sites. At site 85, the characteristic values of these three properties were sufficient for the timber to achieve the requirements for the C24 strength class. Conversely, timber from sites 339, 449 and 5313 only achieved the requirement for the C14 strength class. For the overall resource (i.e. assigning a double weighting to sites 412, 449, 2,792 and 2,946), optimal yields for C24 and TR26 were 27.6 and 29.2 %, respectively, while the yield for C27 was 19.4 % (Table 7). For these three higher strength classes, it was possible to assign the majority of the remaining material to the C16 strength class, which resulted in an overall optimum yield of structural timber in excess of 95 %.

3.4 Segregation using tree and log-level measurements

As the threshold stress wave velocity for logs increased from 2.8 km s^{-1}, there was a monotonic increase in the mean value of MOE$_{\mathrm{PB}}$ of the timber sawn from those logs which had a velocity greater than this threshold value (Fig. 3). As expected, there was a corresponding decrease in the proportion of the population of logs which had a stress wave velocity greater than this threshold. If no segregation had

Table 7 Proportion of timber meeting the requirements for different strength classes based on optimal grading. The factor k_v=1.12 has been applied to the required characteristic value for bending strength and the 0.95 factor applied to the characteristic value of modulus of elasticity

Strength class	Required values			Yield (%)
	$f_{m,k}$ (N mm^{-2})	ρ_k (kg m^{-3})	$E_{0,\mathrm{mean}}$ (kN mm^{-2})	
TR26/C16				
TR26	25.3	370	10.45	27.6
C16	14.3	310	7.60	69.1
				96.7
C27/C16				
C27	24.1	370	11.40	19.4
C16	14.3	310	7.60	80.6
				100.0
C24/C16				
C24	21.4	350	10.45	29.2
C16	14.3	310	7.60	66.1
				95.3
C22/C14				
C22	19.6	340	9.50	57.6
C14	12.5	290	6.65	42.4
				100.0
C20/C14				
C20	17.9	330	9.03	74.9
C14	12.5	290	6.65	11.8
				86.7
C18	16.1	320	8.55	92.1
C16	14.3	310	7.60	100.0

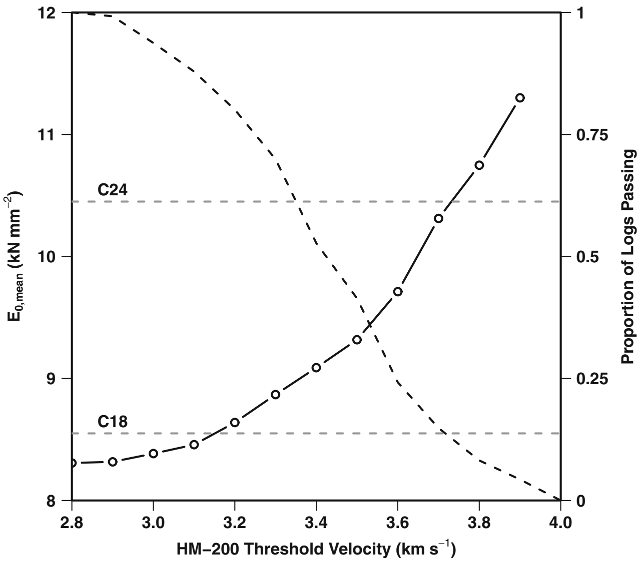

Fig. 3 Effect of log segregation using the HM-200 on the characteristic stiffness of sawn timber. The *dashed line* indicates the proportion of logs with an acoustic velocity greater than or equal to a particular threshold. The characteristic timber stiffness values for the C18 and C24 strength classes are indicated with *dashed grey lines*

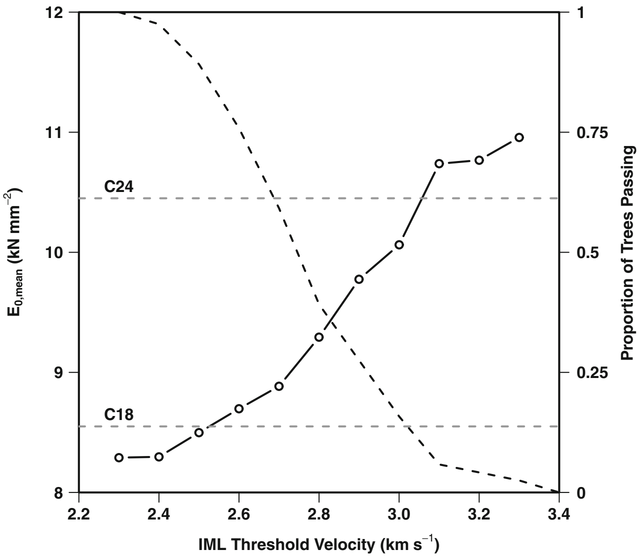

Fig. 4 Effect of tree segregation using the IML Hammer on the characteristic stiffness of sawn timber. The dashed line indicates the proportion of trees with an acoustic velocity greater than or equal to a particular threshold. The characteristic timber stiffness values for the C18 and C24 strength classes are indicated with *dashed grey lines*

been applied, then the timber cut from this population of logs would have had a value of MOE_{PB} that was sufficient for it to achieve the requirements of the C16 strength class. In order for a sawmill to produce timber which has a mean value of MOE_{PB} sufficient to meet the requirements for the C18 strength class with theoretical 0 % grading machine rejects (assuming that the strength and wood density requirements have been met), they would need to set a threshold stress wave velocity for logs of approximately 3.3 kms^{-1}. At this threshold, approximately 30 % of logs from the current population would be rejected. Segregation is also possible on standing trees (Fig. 4). In this case, a threshold stress wave velocity for standing trees of approximately 2.5 kms^{-1} would be required if the goal was to produce structural timber that met the requirements for the C18 strength class without machine rejects. Approximately 20 % of the trees in the current population would fail to meet this threshold. Log and tree segregation to produce timber that is able to meet the stiffness requirement for the C24 strength class would require threshold stress wave velocities of approximately 3.7 and 3.1 kms^{-1}, respectively. In both cases, approximately 90 % of trees and logs would fail to meet this threshold.

4 Discussion

This study has shown that, overall, structural timber produced from UK-grown Sitka spruce meets the requirements for the C16 strength class as defined in EN 338 (CEN 2009a). It has also shown that there is a large amount of variation in the mechanical properties of Sitka spruce timber, both within and between trees, and that modest amounts of higher strength class material (e.g. C22, C24 and C27) do exist in the UK Sitka spruce resource. However, it is important to note that the values presented in Table 7 are optimum yields and that actual yields achieved in practice would be lower. This difference arises from the lack of a perfect correlation between values of the key grade determining property (in this case wood stiffness) measured by a grading machine and those measured in the laboratory, coupled with the requirement in EN14081-2 that places a limit on the proportion of pieces that can be ‘wrongly’ upgraded. Despite the fact that over 30 % of the resource appears to be C24 and the optimal yield of the C24/C16 grade combination is in excess of 90 %, UK Sitka spruce timber is rarely, if ever, graded using a C24/C16 setting even though such settings do exist for a number of different grading machines (see EN14081-4; CEN 2009b). The reason given for this is that the low yields of C24 and an overall increase in the total number of rejects makes it uneconomic to do so, particularly when the price differential between C16 and C24 is small. However, as grading machine technology improves and machines are better able to measure wood stiffness (e.g. through measuring both stress wave velocity and density), actual yields of higher strength class material will approach the optimum yields, which in turn may mean that it becomes economic to target these higher grades.

The study has also shown that various approaches can be used to segregate stands, trees and logs based on the mechanical properties of the sawn timber that they will yield.

While such segregation may not be necessary if the objective of a sawmill is to produce C16 structural timber from the current Sitka spruce resource that exists in the UK, some type of segregation may be necessary prior to processing in the sawmill if the goal is to produce higher strength class timber, or if in the future there is a negative shift in the quality of the wood raw material resource. Segregation can either be based on site, stand and tree factors or on the use of portable acoustic tools. Both approaches were tested in this study and equations were developed to predict the average timber properties for sites, logs and individual boards. In general, equations based on site, stand, tree and log parameters performed similarly to those based on stress wave velocity measurements. The former have the advantage of being based on information that is routinely collected as part of a stand forest inventory or is held in a stand record system, but they also provide additional insight into the factors that affect the properties of structural timber and how these are influenced by forest management. Therefore, they could be used in conjunction with other information for strategic planning at a forest or regional level, but may require modification to improve their applicability to a wider range of stands, e.g. greater age or geographical distribution.

Arguably, the simplest of these segregation approaches is to calculate the mean live crown ratio for a stand as this is significantly and negatively associated with the mean modulus of elasticity of sawn timber from the stand. This negative association between live crown ratio and timber stiffness observed in this study was not unexpected as proximity to the live crown has been suggested as one possible mechanism controlling the transition between juvenile and mature wood (Larson 1969; Zobel and Sprague 1998; Lachenbruch et al. 2011). Larson (1969) postulated that trees with longer crowns will have a larger zone of juvenile wood in the upper stem and a lower percentage of latewood in the lower part of the stem than trees with shorter crowns. Live crown ratio generally decreases with increasing stand age and stocking density, both of which have been shown to be positively associated with the stiffness of Sitka spruce timber (Moore et al. 2009a, 2012). In stands of a similar age, trees with longer crowns have larger branches (Auty et al. 2012), which yields timber with larger knots (Moore et al. 2009a). Timber stiffness was also negatively associated with DBH and elevation, but positively associated with breast height age. The latter association has been shown for a wide range of species (e.g. Cown and McConchie 1982; Clark et al. 1996; Duchesne 2006), including Sitka spruce (Moore et al. 2012), and it was assumed that restricting the age range of the stands in this study would reduce any confounding effects of stand age. However, even over the relatively small age range of stands in this study there was still a positive association between stand age and timber stiffness, indicating that a reduction in rotation length could have negative consequences for timber stiffness.

The negative association between stiffness and both DBH and elevation observed in this study was not unexpected as the earlier study on standing trees by Moore et al. (2009b) obtained a similar result. A negative relationship between MOE and DBH was also observed for black spruce (*Picea mariana* Mill.) growing in eastern Canada by Lei et al. (2005), but interestingly they found a positive relationship between MOE and crown length. The variation in log and timber properties with log position that was observed in this study produced two seemingly contradictory results. $\mathrm{MOE}_{\mathrm{dyn}}$ of logs decreased with increasing log height up the stem, while there was a small increase in $\mathrm{MOE}_{\mathrm{PB}}$ of sawn timber with increasing log height (position) up the stem. In both cases, it is important to consider that the start of the butt log was at 1.3 m above the ground, rather than at the base of the tree. This means that the low stiffness region of the tree, which is located near the base of the stem (Maun 1992; McLean 2007), would have been avoided. However, it is more likely that the trend of increasing timber stiffness with height up the stem, which runs counter to most results reported in the literature (e.g. Cown 1999; Brüchert et al. 2000; Brüchert and Gardiner 2006), is due to the smaller sample size of boards from upper logs. More detailed investigations of the trends in timber stiffness with log height in Sitka spruce are required because this was not a key objective of the current study.

Stress wave measurements made on standing trees can be successfully used to compare stands on the basis of the properties of the structural timber that they will yield. While there is a strong relationship between the mean value of $\mathrm{MOE}_{\mathrm{dyn,tree}}$ and the mean timber stiffness at a stand level, approximately 75 % of the variation in timber stiffness is within a stand. Segregation at the stand level will not capture this variation; however, it may be used by a forestry company during a pre-harvest assessment or by prospective purchaser when evaluating a standing sale (Wang et al. 2007). At the time of harvest, stress wave measurements could be used to segregate individual trees based on their wood properties. While this is unlikely to be cost-effective if measurements are made with a hand-held tool, as was the case in this study, it could be cost-effective if the technology was incorporated into a harvesting machine (Amishev and Murphy 2008). Modern harvesting machines are already equipped with stem measurement and bucking software that determine the optimal cross-cutting points based on external stem characteristics (Uusitalo et al. 2004) and a prototype machine that also includes a time-of-flight stress wave instrument is currently under development (Timber Sonics Ltd, Lenzie, Scotland, personal communication). This would enable log making decisions to be made on the basis of both tree geometry and information about internal wood properties. The relationships between timber stiffness and stress wave velocity measurements made on trees and logs or with other site, stand and tree factors can also be used to inform tree breeding efforts focused on improving timber stiffness (e.g. Cherry et al. 2008; Vikram et al. 2011).

Sawmills could use portable acoustic tools to obtain an estimate of the mean value of $MOE_{dyn,log}$ for a particular stand. Again, this ignores the within-stand variation and it could be more advantageous for a sawmill to measure the stress wave velocity on every log entering the mill and to segregate them into groups based on their stiffness (automated systems for doing this are already available). If these measurements could be combined with shape scanning and X-ray scanning, then logs could be sorted more efficiently. Riddout et al. (1999) found that sorting logs using a combination of branch size and stress wave velocity measurements was more effective than sorting based on stress wave velocity alone. X-ray scanning of logs would provide information on branch characteristics as well as wood density variation (Rinnhofer et al. 2003), which could be used to improve the prediction of $MOE_{dyn,log}$ for an individual log as well as the relationship between $MOE_{dyn,log}$ and mean timber MOE. The large amount of unexplained variation in this relationship is assumed to be due to the following factors: (1) the overall static MOE of the log is not equivalent to the arithmetic average of the structural timber cut from it; (2) density differences between logs, mostly reflecting differences in heartwood content, are ignored; and (3) the relationship between static MOE and $MOE_{dyn,log}$ depends on log diameter (Wang et al. 2004a). While it is not feasible to address this first point, density information obtained from an X-ray scanner and information on log diameter obtained from a shape scanner could be used to address the latter two points.

A number of authors have already shown that there is a strong relationship between the mean value of $MOE_{dyn,log}$ for groups of logs and the mean stiffness of the resulting sawn timber (e.g. Green and Ross 1997; Ross et al. 1997; Tseheye et al. 2000; Carter et al. 2005; Edlund et al. 2006). Even within a log stiffness class, there will be considerable variation in timber stiffness due to the radial variation that exists within a log (Walker and Butterfield 1995; Zobel and Sprague 1998; Xu and Walker 2004). This is apparent in the current study through the significance of the ring width term in the equations to predict the stiffness of individual boards. Ring width is a surrogate for radial position, with wider rings occurring near to the pith and narrower rings occurring closer to the bark. In low velocity logs, timber cut from near the pith (i.e. within the juvenile core) will be less stiff than timber cut from further out and is more likely to be rejected when the timber is strength graded than timber cut from within the juvenile core of a higher stiffness log. If this material is not segregated out at an early stage in a sawmill, then money is spent processing timber that is ultimately rejected. Conversely, if the entire log is rejected based on a stress wave velocity measurement, then stiffer timber cut from the outerwood is also rejected even though it may have passed the strength grader. Therefore, a better option financially could be to alter the cutting patterns for lower stiffness logs in order to produce timber that will not be rejected during the grading process. Recent research by Searles (2012) showed the altering the cutting pattern for these low stiffness logs improved the grade recovery of sawn timber without sacrificing volume recovery and could, therefore, increase the value recovery from these logs.

In conclusion, this study has shown that structural timber cut from UK-grown Sitka spruce forests inherently meets the requirements for the C16 strength class. Timber stiffness was found to be associated with a number of site, stand and tree factors, and knowledge of these factors can assist with segregation of the current resource as well as informing decisions about the management of the future resource. The study has also demonstrated the utility of portable acoustic tools for increasing the stiffness of sawn timber by segregating out individual trees and logs that will yield low stiffness timber. This technology could be applied if UK sawmillers wish to produce higher strength class timber or there is a negative shift in the quality of the resource. Further research is required to investigate how such segregation approaches could be applied in practice and the economic implications of segregation.

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