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Predicting structural timber grade-determining properties using acoustic and density measurements on young Sitka spruce trees and logs

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Abstract: In Ireland, most structural timber from Sitka spruce (*Picea sitchensis* [Bong.] Carr.) is machine graded into C16 strength class. However, timber from early thinnings is mostly used for non-structural applications. There is an increased demand for structural timber, and timber from young trees could contribute to wood supply. However, this timber has lower mechanical properties than mature timber. In order to pre-sort the resource for structural application of wood from thinning, the possibilities of acoustic and density (D) measurements on young trees and logs have been investigated. The stress wave velocity (SWV) and pin penetration depth (PD) were measured on standing trees, which were then felled and cut into 10-m-long logs and subsequently into 3-m-long logs. Fundamental frequency was measured on logs. Finally, the logs were processed into boards, which were tested in accordance with EN 408 to obtain modulus of elasticity (MOE) in bending, bending strength (BStr) and D. The results showed good relationships between timber properties and acoustic and D measurements. Models for predicting grade properties of timber from thinnings are presented. Pre-sorting of young Sitka spruce trees and logs helped obtain higher C16 yields.

Keywords: acoustics, bending strength, modulus of elasticity, pre-sorting, timber properties, wood density

Introduction

In the Republic of Ireland, Sitka spruce (*Picea sitchensis* [Bong.] Carr.) is the predominant tree species occupying 52.4% of the total forest area (Forest Service 2016). Sitka spruce plantations in Ireland are mostly managed over rotation lengths of 35–45 years and smaller trees are removed during thinning operations with a view to increasing the volume of utilisable timber at the end of rotation period. From the total softwood roundwood available for processing in 2015, 61% of logs were used for structural timber production. However, timber from thinning operations is mostly used for non-structural applications such as pulp, pallets, fencing, chips and pellets. In view of the increasing demand for more sustainable building materials, better-quality timber from thinnings could be allocated and used for structural applications. In accordance with EN 338 (CEN 2016a), structural softwood timber is assigned to C-type strength classes based on modulus of elasticity (MOE) in bending, bending strength (BStr) and density (D), which are known as grade determining. Most of the timber produced in Ireland is graded into C16 strength class (Raftery and Harte 2014) with a pass rate exceeding 90% for C16/reject grading setting.

Non-destructive techniques (NDTs) for predicting strength grade relevant properties have been developed in the last few decades (Knuffel 1988; Arriaga et al. 2012; Casado et al. 2012; Ross 2015). There are several established NDT methods applied in sawmills for grading of timber boards (Ridley-Ellis et al. 2016), such as the longitudinal stress wave propagation, which are suitable for the evaluation of timber quality on standing trees and logs (Legg and Bradley 2016). The stress wave (acoustic) velocity (SWV) can be measured by the resonance method, in which the fundamental frequency is considered, and the time-of-flight method (TOF), which measures the time required for a wave to travel between two sensors (Arriaga et al. 2014, 2017; Denzler and Weidenhiller 2016). The former is typically used on logs, while the latter one on standing trees (Wang 2013). In recent years, handheld devices for acoustic measurements have been widely accepted by the forest industry for quality assessment (Carter et al. 2005; Mochan et al. 2009). Early segregation of trees and logs based on dynamic MOE (MOE_{dyn})

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determination can improve the efficiency of the wood processing chain and optimise allocation of raw material. Whole stands could be selected for production of desired end-products depending on the prediction of grade-determining properties based on acoustic tools. Although there are other means to this purpose, for example, traditional mechanical tests or visual inspection, acoustic technology has the advantages of being fast, relatively cheap and, most importantly, it can easily be automated.

Acoustic measurements on logs have been frequently described (Tsehaye et al. 2000; Wang et al. 2004; Lindström et al. 2009; Yin et al. 2011; Baltrušaitis and Aleinikovas 2012; Denzler and Weidenhiller 2016). However, stress wave propagation in the stem of a standing tree is not fully understood (Wang et al. 2004; Zhang et al. 2011; Searles 2012). Such studies were performed based on results obtained from strength grading machines from boards without direct measurement of grade-determining properties (Brüchert et al. 2011; Rais et al. 2013; Fischer et al. 2015). Auty and Achim (2008) applied acoustic tools on Scots pine standing trees in Scotland to predict the mechanical properties of small clear specimens and concluded that SWV can be a good predictor of both MOE and BStr. Moore et al. (2008) reported very strong relationships between the MOE_{stat} and MOE_{dyn} for British-grown Sitka spruce sawn timber. A moderately strong relationship between the MOE_{stat} measured on sawn timber and the log MOE_{dyn} was also reported. The remaining, not explained variation (VA) was attributed to the radial and circumferential VAs in wood properties within a log and the log-to-log VA in green D (D_{green}). Brüchert et al. (2011) investigated the possibility of wood quality prediction from standing tree to sawn timber of Norway spruce [*Picea abies* (L.) Karst] and Scots pine (*Pinus sylvestris* L.) stands in Sweden and Germany. The MOE_{dyn} of dry boards was measured and compared with tree and log MOE_{dyn} measured using different NDT tools. A strong relationship between the dried boards' MOE_{dyn} and log MOE_{dyn} and D_{basic} was found. Rais et al. (2013) explored the relationship between MOE_{dyn} at different stages of the wood processing chain for Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] in Germany. The authors presented a model for MOE_{dyn} prediction at each stage of the production chain (standing trees, long logs, short logs and boards) and pre-grading at the levels of a standing tree and logs was performed.

Moore et al. (2013) found very strong correlations between the MOE_{dyn} obtained on standing trees and logs and mean values of all timber grade-determining properties of Sitka spruce in the UK. In the quoted work, the overall VA in MOE, D and BStr of timber boards was attributed to differences between trees within a stand (36.2, 51.1 and 25.2%, respectively) and boards within a log (35.3, 24.9 and 51.9%, respectively). Models for predicting the log and timber properties at the level of stand, log and board were developed. However, in the calculation of MOE_{dyn} of trees and logs, timber D was not measured and it was assumed to be constant. Searles (2012) found that 15.9% of the logs were allocated to incorrect stiffness grades because of the assumption of a constant D of the logs. The Pilodyn penetration and resistance drilling measurement are very good predictors of timber D (Cown 1978; Oliveira et al. 2017). Chen et al. (2015) found very strong relationships between MOE_{dyn} based on acoustic measurements and Pilodyn penetration and MOE_{stat} of small clear wood specimens taken from increment cores at 1.3 m above the ground level.

In the present initial study, the application of acoustic instruments was tested for timber quality evaluation of Irish-grown Sitka spruce. The focus is on the identification of key approaches and techniques in the prediction of properties of sawn timber, which are relevant for grade determination. In this context, acoustic and D measurements are performed at the levels of trees, logs and boards. The challenge is to estimate the final wood quality as early as possible in the production chain. Green and dry boards were considered, in which the moisture content (MC) is above the fibre saturation point (FSP) and at ≈12%, respectively. Almost 900 boards were destructively tested to obtain all grade-determining properties by traditional methods. The strength classes for softwoods, based on edgewise bending tests, are defined in EN 338 (CEN 2016a) for MOE in bending parallel to the grain, BStr and D. Moreover, MOE_{dyn} data were collected by a combination of acoustic and D measurements on each tree and log. The TOF method was, in focus, applied at tree levels, while the resonance-based method was applied at the levels of logs and boards. As most of the structural timber in Ireland is sawn from butt logs, the log positions along the tree stem are taken into consideration in terms of the relationship between log MOE_{dyn} and the mechanical properties of sawn timber. Altogether, pre-sorting of trees and logs was undertaken in order to explore the possibilities of increasing C16 yield of young Sitka spruce timber.

Materials and methods

Experimental site: The study was conducted at an even-aged Sitka spruce plantation forest (latitude 53° 59′ N, longitude 7° 46′ W, elevation 100 m) situated in County Leitrim, Republic of Ireland. The plantation was established in 1992 and the trees were planted at different planting densities, ranging between 1550 and 3700 stems ha^{-1}, which appeared to be arbitrarily located within the site. In a parallel study (Simic et al. 2017), the influence of planting D on timber MOE measured using NDTs was studied. Twelve plots were selected from the forest. The plots were situated on an east facing slope ranging from 8 to 22% gradient with surface water gley soil that was previously a rough grazing land. Each plot was 8 m × 25 m (0.02 ha) in size with the longer side orientated in the slope direction and within the interior of the stand avoiding patches of windthrown trees.

Fieldwork: In 2015, when the stand was 23 years old, diameters at breast height (DBH: 1.3 m) were measured in each plot. Acoustic velocities of all trees in each plot with a diameter greater than 10 cm were measured using a Hitman ST300 instrument (Fibre-gen Ltd., Christchurch, New Zealand) on the south and north side of the tree, with approximately 1.3-m distance between the probes. The transducer probe was placed approximately 0.5 m from the ground level while the receiver probe was located at a height of 1.8 m. A small piece of bark at DBH on the south side of a tree was removed and the penetration depth (PD) was measured using a Pilodyn 6J Forest instrument (Proceq SA, Schwerzenbach, Switzerland) with a 2.5 mm pin. Both measurements were taken on 345 trees in total. All the trees within the plots were assessed visually for the straightness of the bottom 6 m of the stem using a seven-point scoring system based on the UK Forestry Commission's Protocol (Macdonald et al. 2001) with modifications to the sample size and tree diameters at the time of felling. The scoring system signifies the maximum length of straight logs, with score 1 for no straight logs available and score 7 for at least 5 m of straight log available from the bottom 6 m of the stem. Trees with poor stem form were ignored. The dominant classes were defined based on DBH within a plot, and trees were equally distributed in all three dominance groups: sub-dominant (lower 1/3 of DBHs), co-dominant (middle 1/3 of DBHs), and dominant (upper 1/3 of DBHs). From each plot six trees were randomly selected for felling according to the indicated dominance categories for each of the 12 plots. Overall, 72 trees were felled. After felling, each tree was delimbed and a 10-m-long log was cut starting from 25 cm above the ground level. The log fundamental frequency was measured using the MTG instrument (Brookhuis Applied Technologies, Enschede, The Netherlands) on the forest ground. Then, each 10-m-long log was cross cut into four 10-cm-thick discs and three 3-m logs as illustrated in Figure 1. After extraction from the forest, the fundamental frequency of the 3-m logs was measured using the MTG instrument in the sawmill yard. The total number of 3-m logs was 213 as three logs were lost during the work in the forest. The 3-m logs were colour-coded and numbered to facilitate tracking during processing. A total of 198 3-m logs were sawn into 904 boards having one of two cross-sectional dimensions, 44 mm × 100 mm or 35 mm × 75 mm. A total of 15 logs that had a small end diameter (d_{small}) less than 14 cm were excluded. Four 10-cm-thick discs were extracted from each tree at the following heights measured from the ground level to the disc's midpoint: 0.30, 3.43, 6.56 and 9.69 m. The mass and volume of the discs were measured within 48 h of the extraction from the 10-m logs and green densities (D_{green}) of 288 discs were calculated.

Estimation of MOE$_{dyn}$ of trees and logs: Tree MOE$_{dyn}$ ($E_{dyn,tree}$) in MPa was estimated by Eq. 1 based on previous studies on Norway spruce (Costa E Silva et al. 2000; Chen et al. 2015):

$$E_{dyn,tree} = 1/P(10^4 v^2), \tag{1}$$

where P is the penetration depth (PD) (mm) obtained using the Pilodyn instrument and v is mean stress wave velocity (SWV) (km s^{-1}) between the south and north measurement points obtained using the Hitman ST300 instrument.

The MOE$_{dyn}$ of 10-m logs ($E_{dyn,10m\ log}$) and 3-m logs ($E_{dyn,3m\ log}$) was estimated by Eq. 2 (Ross 2015):

$$E_{dyn} = \rho \cdot 4 \cdot l^2 \cdot f^2, \tag{2}$$

where ρ is the density (D), l is the length and f is the fundamental frequency of the log obtained using the MTG instrument. The D of each 10-m log was calculated as the average of the four discs cut from that log, while the D of each 3-m log was calculated as the average of the discs cut from each end of the log.

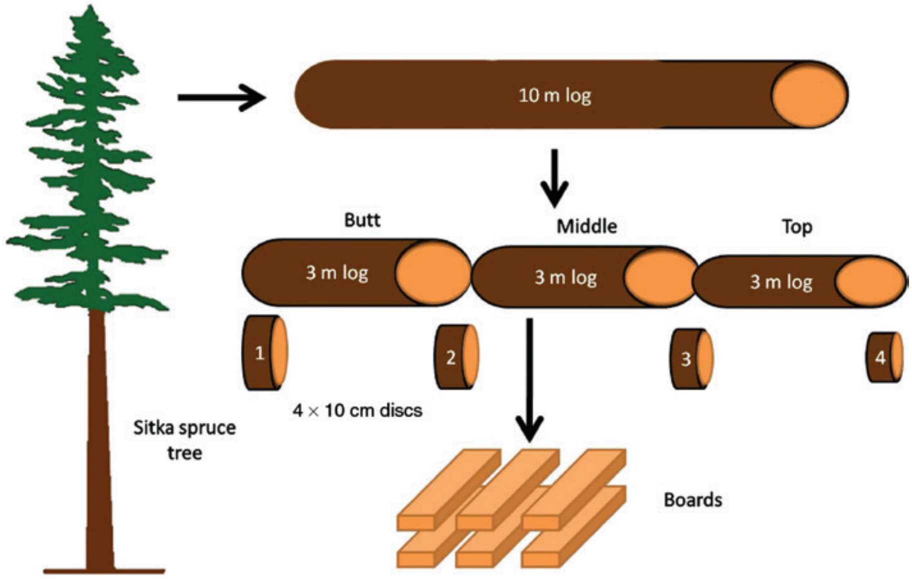

Figure 1: Acoustic measurements at different stages of the wood processing chain from a standing tree to sawn timber.

Sawn timber measurements: The MOE$_{dyn}$ of green (above FSP) timber boards ($E_{dyn,green}$) was calculated from the fundamental frequency (f_{green}) and D$_{green}$ ($\rho_{mtg,green}$) using Eq. 2. Fundamental frequency and mass were measured by means of the MTG timber grader connected with a balance. After kiln drying to an MC of 18±2%, timber boards were delivered to the National University of Ireland Galway Timber Engineering Laboratory, where they were stored at 20±2°C and 65±5% relative humidity (RH). Drying of the boards was monitored using a moisture meter in accordance with EN 13183-2 (CEN 2002a). When the boards reached an MC of 12±2%, the cross-sectional dimensions were measured at three points along the length. The fundamental frequency (f_{12}) and D ($\rho_{mtg,12}$) were measured again (MTG timber grader) and the MOE$_{dyn}$ of the timber boards ($E_{dyn,12}$) at 12% MC was calculated using Eq. 2. Then, testing in accordance with EN 408 (CEN 2012) was conducted to obtain the timber MOE in bending (E_m), BStr (f_m) and D (ρ). The timber MOE and BStr were calculated from the load and deflection measurements obtained in the four-point bending test by means of a Dartec 500 kN Servo Hydraulic Testing Machine. The deflection measurements for the determination of local MOE ($E_{m,local}$) and global MOE ($E_{m,global}$) were performed by means of a linear variable differential transformer (LVDT) and a pair of string potentiometers, respectively. After strength testing, timber D was determined by gravimetry on 20-mm-long small clear wood specimens of the full cross-section that were cut as close as possible to the fracture location. MC was determined by the oven-dry method described in EN 13183-1 (CEN 2002b). The data for seven boards from the total sample of 904 boards were lost due to technical issues during testing.

Data analysis: Data analysis was carried out via the IBM SPSS Statistics (IBM, Armonk, NY, USA) software. In Table 1, the following data are presented: mean values (average values, avg), standard deviations (SD), sample sizes (*n*) of trees and logs and data from the acoustic measurements at each level in the wood processing chain. The results for 3-m logs are separately presented for the segments butt, middle and top parts of the stem.

The relationships between MOE$_{dyn}$ and the grade-determining properties are described by linear regression. The tree level models are based on Pilodyn PD and tree MOE as input variables (x) and mean values of grade-determining properties as response variables (y). At the 3-m and 10-m-log levels, y-data are mean values that were calculated for all boards cut from each log, while log fundamental frequency, log D measured on discs and log MOE$_{dyn}$ data served as input variables (x). Mean values were weighted according to the board volume proportion in total log volume to account for different board sizes. The assumptions for linear models were tested and confirmed. The relationships between the average data and the acoustic measurements are presented in Table 2. The global MOE of dry boards is presented along with the acoustic input variables at the board level.

The effects of pre-sorting of trees and logs based on MOE$_{dyn}$ on the C16 yields of the sawn timber were modelled. The data were sorted in descending order, and the lowest 10% of the values were excluded. Then, the exclusions were gradually increased in 10% steps from the original sample, and proportions of timber that met the requirements for C16 were recorded. The proportion of C16 timber was calculated based on the procedures for optimum grade determination described in EN 14081-2 (CEN 2010). According to this standard, the optimum grading is based on the knowledge of all relevant data (MOE, BStr and D) and maximum yield for the highest grade. Each board assigned to the optimum grade shall meet the requirements for that grade from EN 338:2016 adjusted by the factors for MOE (k_v 0.95) and BStr (k_v=1.12) from EN 384 (CEN 2016b). The maximum number of pieces that met these requirements was identified by filtering the data set according to EN 14081-2 and the proportion of C16 timber was calculated. Adjustment factors for the reference MC of 12% and 150-mm timber cross-sectional height (k_h) were applied. For the MOE calculation parallel to the grain ($E_{m,0}$), the local MOE ($E_{m,local}$) was used. The term MOE refers to bending parallel to the grain (MOE$_{stat}$).

Table 1: Tree and log characteristics and acoustic measurements at different stages.

Parameter	*n*	Mean	SD
Trees			
DBH (cm)	72	22.35	4.28
Height (m)	72	19.75	1.46
P (mm)	72	17.15	2.13
v (km s^{-1})	72	3.3497	0.2719
$E_{dyn,tree}$ (MPa)	72	6722	1537
10-m logs			
ρ (kg m^{-3})	72	836	43
$f_{10m\ log}$ (Hz)	72	166	8.33
$E_{dyn,10m\ log}$ (MPa)	72	9230	1054
3-m logs			
All			
$d_{small,all}$ (cm)	195	18.98	3.79
$\rho_{3m\ log,all}$ (kg m^{-3})	195	829	50.16
$f_{3m\ log,all}$ (Hz)	195	515	30.66
$E_{dyn,3m\ log,all}$ (MPa)	195	7941	1069
Butt			
$d_{small,butt}$	72	20.67	3.86
$\rho_{3m\ log,butt}$ (kg m^{-3})	72	804	45.26
$f_{3m\ log,butt}$ (Hz)	72	502	32.06
$E_{dyn,3m\ log,butt}$ (MPa)	72	7321	1072
Middle			
$d_{small,middle}$	67	18.95	3.41
$\rho_{3m\ log,middle}$ (kg m^{-3})	67	828	42.80
$f_{3m\ log,middle}$ (Hz)	67	534	23.89
$E_{dyn,3m\ log,middle}$ (MPa)	67	8519	915
Top			
$d_{small,top}$	56	16.79	2.99
$\rho_{3m\ log,top}$ (kg m^{-3})	56	861	46.41
$f_{3m\ log,top}$ (Hz)	56	510	24.51
$E_{dyn,3m\ log,top}$ (MPa)	56	8058	783
Green boards			
$\rho_{mtg,green}$ (kg m^{-3})	897	831	174
f_{green} (Hz)	897	527	42.98
$E_{dyn,green}$ (MPa)	897	7659	1365
Dry boards			
$\rho_{mtg,12}$ (kg m^{-3})	897	386	32.46
f_{12} (Hz)	897	755	62.09
$E_{dyn,12}$ (MPa)	897	7939	1326
$E_{m,global}$ (MPa)	897	7030	1382
$E_{m,local}$ (MPa)	897	7910	2027
f_m (MPa)	897	31.02	8.72
ρ (kg m^{-3})	897	377	33.92

Table 2: Results of linear regression analysis y = ax + b for the different stages in the timber processing chain.

Level	y	x	a (±StE)	b (±StE)	*n*	R²	Model
Tree and 10-m-long log	$E_{m,local}$	v (km s^{-1})	3727 (±533)	−4107 (±1792)	72	0.41	1
		P (mm)	−355.91 (±77.98)	14 483 (±1348)	72	0.22	2
		$E_{dyn,tree}$	0.762 (±0.83)	3257 (±569)	72	0.55	3
		$f_{10m\ log}$ (Hz)	129.64 (±16.58)	−13 138 (±2755)	72	0.47	4
		$\rho_{10m\ log}$ (kg m^{-3})	16.68 (±3.96)	−5553 (±3317)	72	0.20	5
		$E_{dyn,10m\ log}$	1.221 (±0.104)	−2888 (±966)	72	0.66	6
	f_m	v (km s^{-1})	11.71 (±2.29)	−6.18 (±7.71)	72	0.27	7
		P (mm)	−1.61 (±0.28)	60.67 (±4.92)	72	0.31	8
		$E_{dyn,tree}$	2.72×10^{-3} ($\pm0.35\times10^{-3}$)	−14.73 (±2.39)	72	0.47	9
		$f_{10m\ log}$ (Hz)	0.385 (±0.075)	−30.86 (±12.42)	72	0.28	10
		$\rho_{10m\ log}$ (kg m^{-3})	7.62×10^{-2} ($\pm1.45\times10^{-2}$)	−30.60 (±12.17)	72	0.28	11
		$E_{dyn,10m\ log}$	4.09×10^{-3} ($\pm0.49\times10^{-3}$)	−4.74 (±4.56)	72	0.50	12
	ρ (kg m^{-3})	v (km s^{-1})	48.51 (±11.93)	224.16 (±40.10)	72	0.19	13
		P (mm)	−11.48 (±1.00)	583.57 (±17.22)	72	0.66	14
		$E_{dyn,tree}$	1.43×10^{-2} ($\pm1.60\times10^{-3}$)	290.21 (±11.04)	72	0.53	15
		$f_{10m\ log}$ (Hz)	2.06 (±0.36)	45.25 (±59.28)	72	0.32	16
		$\rho_{10m\ log}$ (kg m^{-3})	0.33 (±0.08)	109.68 (±62.64)	72	0.22	17
		$E_{dyn,10m\ log}$	2.05×10^{-2} ($\pm2.39\times10^{-3}$)	197.76 (±22.21)	72	0.51	18
3-m-Long logs	$E_{m,local}$	$f_{3m\ log}$ (Hz)	31.02 (±3.11)	−7634 (±1603)	195	0.34	19
		$\rho_{3m\ log}$ (kg m^{-3})	13.86 (±2.14)	−3150 (±1774)	195	0.18	20
		$E_{dyn,3m\ log}$	1.08 (±0.08)	−226 (±629)	195	0.50	21
	f_m	$f_{3m\ log}$ (Hz)	7.53×10^{-2} ($\pm1.44\times10^{-2}$)	−6.20 (±7.44)	195	0.12	22
		$\rho_{3m\ log}$ (kg m^{-3})	5.77×10^{-2} ($\pm8.56\times10^{-3}$)	−15.21 (±7.11)	195	0.19	23
		$E_{dyn,3m\ log}$	3.13×10^{-3} ($\pm0.39\times10^{-3}$)	7.76 (±3.09)	195	0.26	24
	ρ (kg m^{-3})	$f_{3m\ log}$ (Hz)	0.33 (±0.07)	213.77 (±35.17)	195	0.11	25
		$\rho_{3m\ log}$ (kg m^{-3})	0.22 (±0.04)	198.24 (±34.39)	195	0.13	26
		$E_{dyn,3m\ log}$	1.32×10^{-2} ($\pm1.85\times10^{-3}$)	278.79 (±14.75)	195	0.21	27
Green board	$E_{m,local}$	$E_{dyn,green}$	1.01 (±0.04)	158 (±284)	897	0.46	28
	f_m	$E_{dyn,green}$	3.08×10^{-3} ($\pm0.19\times10^{-3}$)	7.34 (±1.45)	897	0.23	29
	ρ (kg m^{-3})	$E_{dyn,green}$	9.38×10^{-3} ($\pm0.77\times10^{-3}$)	305.35 (±6.01)	897	0.14	30
Dry boards	$E_{m,local}$	$E_{dyn,tree}$	0.60 (±0.04)	4139 (±273)	897	0.18	31
	f_m	$E_{dyn,tree}$	2.34×10^{-3} ($\pm0.19\times10^{-3}$)	16.40 (±1.19)	897	0.15	32
	ρ (kg m^{-3})	$E_{dyn,tree}$	1.48×10^{-2} ($\pm0.61\times10^{-3}$)	285.04 (±3.93)	897	0.39	33
	$E_{m,local}$	$E_{dyn,10m\ log}$	1.04 (±0.06)	−1361 (±564)	897	0.23	34
	f_m	$E_{dyn,10m\ log}$	3.67×10^{-3} ($\pm0.28\times10^{-3}$)	−1.85 (±2.54)	897	0.16	35
	ρ (kg m^{-3})	$E_{dyn,10m\ log}$	2.19×10^{-2} ($\pm0.95\times10^{-3}$)	181.51 (±8.58)	897	0.37	36
	$E_{m,local}$	$E_{dyn,3m\ log}$	0.94 (±0.06)	721 (±438)	897	0.24	37
	f_m	$E_{dyn,3m\ log}$	2.47×10^{-3} ($\pm0.27\times10^{-3}$)	12.08 (±2.06)	897	0.09	38
	ρ (kg m^{-3})	$E_{dyn,3m\ log}$	1.22×10^{-2} ($\pm1.00\times10^{-3}$)	283.83 (±7.75)	897	0.14	39
	$E_{m,local}$	$E_{dyn,12}$	1.07 (±0.04)	−588 (±293)	897	0.48	40
	f_m	$E_{dyn,12}$	3.30×10^{-3} ($\pm0.19\times10^{-3}$)	4.83 (±1.52)	897	0.25	41
	ρ (kg m^{-3})	$E_{dyn,12}$	1.10×10^{-2} ($\pm0.77\times10^{-3}$)	290.42 (±6.22)	897	0.18	42
	$E_{m,local}$	$E_{m,global}$	1.27 (±0.02)	−1031 (±174)	897	0.75	43
	f_m	$E_{m,global}$	4.50 (±0.15)	−0.61 (±1.05)	897	0.51	44
	ρ (kg m^{-3})	$E_{m,global}$	1.04×10^{-2} ($\pm0.74\times10^{-3}$)	304.33 (±5.32)	897	0.18	45

All units in MPa unless otherwise stated. StE, Standard error of the estimate.

Results and discussion

Results at tree level

As seen in Table 2, the SWV measured on standing trees accounted for 41% of the VA in mean values of MOE (avgMOE), 27% VA in avgBStr and 19% VA in avgD of all boards cut from a tree. However, PD was found to be a better predictor of BStr and D than SWV: PD explained 31% VA in avgBStr and 66% VA in avgD (Figure 4a). The good performance of the needle penetration technique was recently described in the literature (Llana et al. 2018b,c). Tree MOE$_{dyn}$ (the combination of SWV and PD) explained

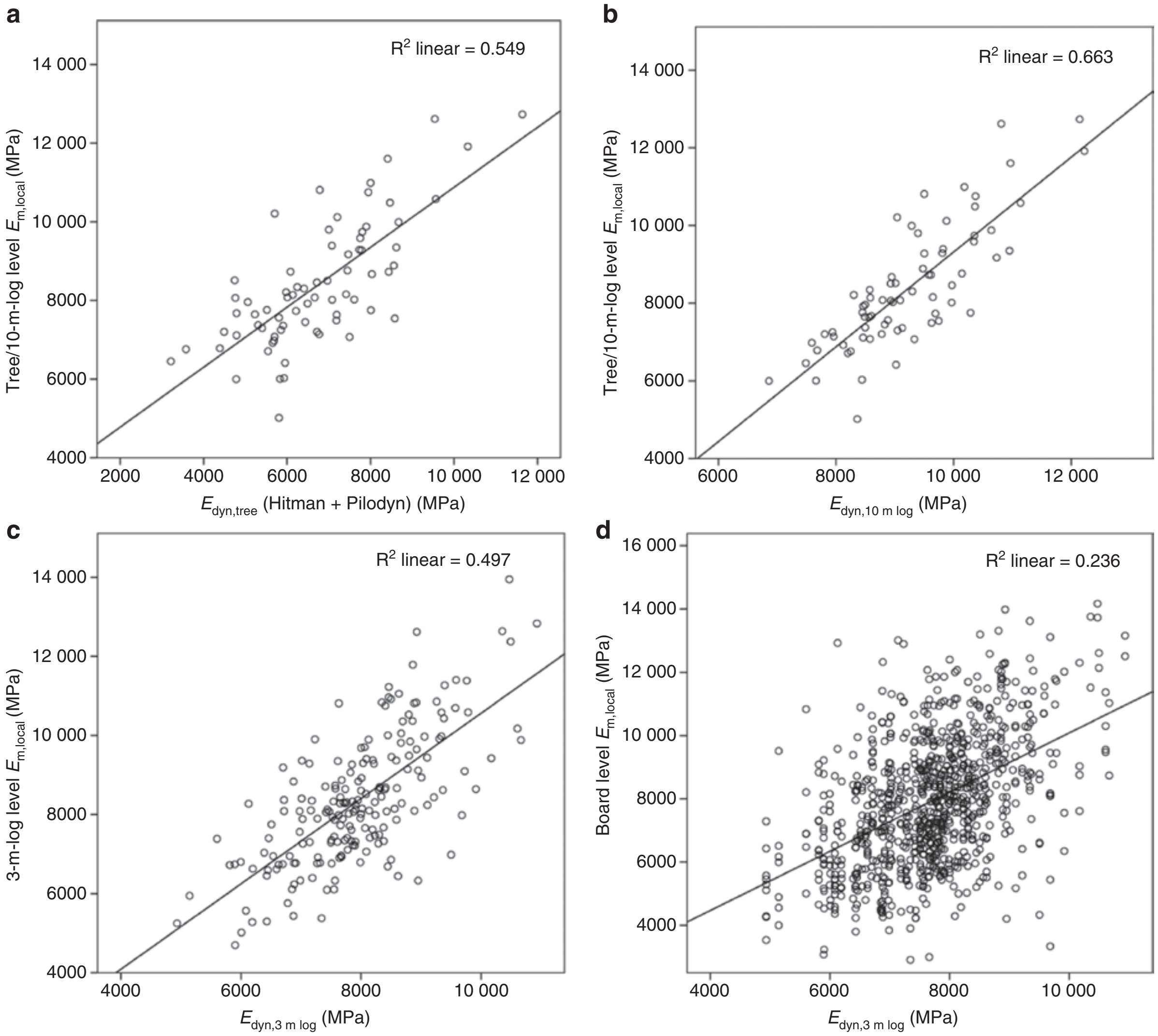

Figure 2: (a) Relationship between MOE_{dyn} of standing trees and MOE_{stat} of sawn timber, (b and c) relationship between MOE_{dyn} of 10-m logs and 3-m logs and MOE_{stat} of sawn timbers, respectively, (d) the relationships at the board level.

55% VA in avgMOE (Figure 2a), 47% VA in avgBStr and 53% VA in avgD of all boards. However, at the individual board level, tree MOE_{dyn} explained only 18% VA in MOE, 15% VA in BStr and 39% VA in D. The difference in the amount of the explained VA in the three properties by tree MOE_{dyn} between tree and individual board levels is due to random VA within a tree. The highest relative difference in VA was seen for BStr, while timber D was the least variable.

Results of 10-m logs

The fundamental frequency of 10-m logs was found to explain 47% VA in avgMOE, 28% VA in avgBStr and 32% VA in avgD of all boards. D_{green} measured on discs accounted for 20% VA in avgMOE, 28% VA in avgBStr and 22% VA in avgD. On the other hand, the combination of fundamental frequency and D_{green} (MOE_{dyn} of 10-m logs) explained 66% VA in avgMOE (Figure 2b), 28% VA in avgBStr and 51% VA in avgD of all boards cut from a 10-m log. Due to the high VA in the grade-determining properties within a log, the R^2 data from the individual board level were reduced by ca. 1/3 in comparison with R^2 at the 10-m-log level. The MOE_{dyn} of 10-m logs accounted for 23% VA in MOE, 16% VA in BStr and 37% VA in D at the board level.

Results of 3-m logs

The MOE_{dyn} measured on the 3-m logs accounted for more VA in avgMOE, avgBStr and avgD than the fundamental frequency or the D_{green} alone. However, the explained VA

Table 3: Coefficient of determination (R^2) for predictive relationships for grade-determining properties of 3-m logs by NDT.

	R^2 for the positions in log		
Properties	**Butt**	**Middle**	**Top**
$E_{m,local}$	0.71	0.53	0.38
f_m	0.48	0.31	0.29
ρ	0.37	0.50	0.27

was less than that for the 10-m logs at 50, 26 and 21% for the avgMOE, avgBStr and avgD, respectively, of the boards. The relationships between the key data at the board level were weaker with the increase in log height within a tree (Table 3). However, the relationship between MOE_{dyn} and timber D peaked for middle logs. At the individual board level, the relationships were weaker, as the MOE_{dyn} of 3-m logs explained only 24% VA in MOE (Figure 2d), 16% VA in BStr and 37% VA in D.

Results at the board level

The MOE_{dyn} of green boards accounted for 46% VA in MOE, 23% VA in BStr and 14% VA in D. The D_{green} of boards accounted only for 4% VA in the D of boards. A very strong relationship was found between the MOE_{dyn} measured on boards in wet and dry conditions ($R^2 = 0.955$, Figure 3a). The MOE_{dyn} obtained on dry boards explained 48% VA in MOE_{local}, 25% VA in BStr and 18% VA in timber D.

The board cross-section size significantly affected the relationship. For 35 mm × 75 mm boards, the MOE_{dyn} accounted for 36% VA in MOE_{local}, 15% VA in BStr and 13% VA in D, while for 44 mm × 100 mm boards, this data increased to 64, 36 and 22% explanation of the VA in MOE_{local}, BStr and D, respectively (Figure 3b). Similar results were obtained for MOE_{dyn} of green boards, which explained the VA at a similar level of accuracy as the measurements on dry boards. Fundamental frequency alone explained less VA in the three properties for both board sizes. The MOE_{global} explained 75.2% VA in MOE_{local} and 51% VA in BStr. The D_{green} of boards ($\rho_{mtg,green}$) accounted only for 4% VA in D of clear wood board, whereas the D_{dry} of boards explained 71% VA in D of clear wood board (Figure 4b).

Influence of pre-sorting

The proportion of timber that met the requirements for C16 strength class was calculated based on the procedures for optimum grade described in EN 14081-2 (CEN 2010).

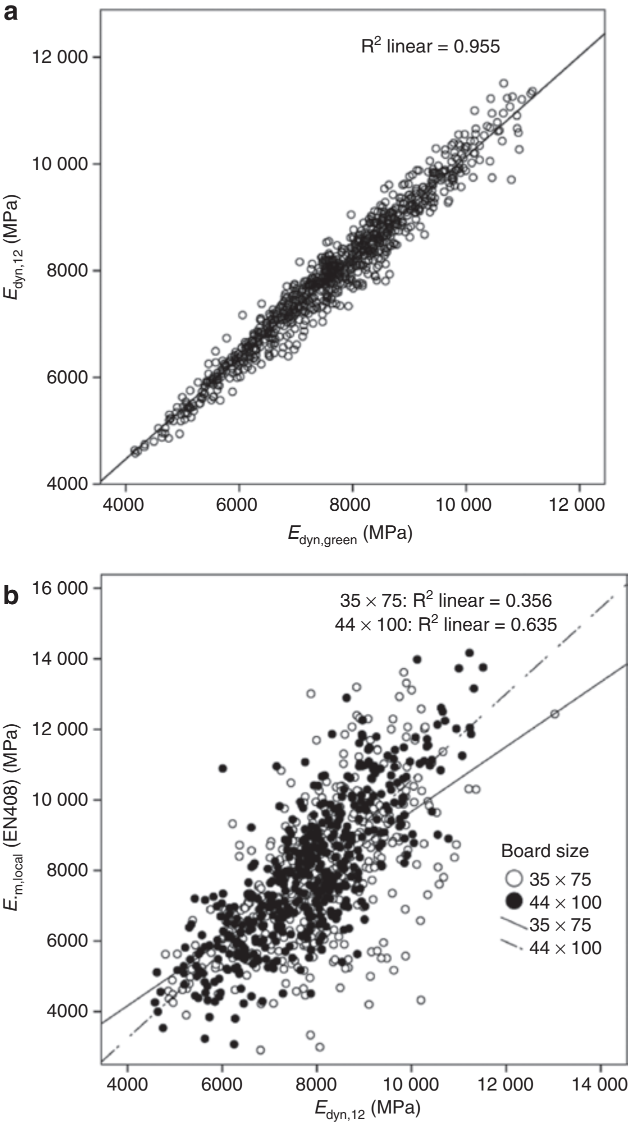

Figure 3: (a) Relationship between MOE_{dyn} of green and dry boards (12% MC) and (b) relationship between MOE_{dyn} and MOE_{stat} measured in accordance with EN 408 for different board sizes.

The results showed that 53% of the boards processed from this young Sitka spruce material can be graded as C16. By pre-sorting of trees and logs, the proportion of timber graded as C16 could be increased to ca. 90% for 10-m logs and 3-m logs, and to 77% for trees (Figure 5). However, by the exclusion of trees and logs that were selected as low-quality material, a certain proportion of boards with higher gross domestic product (GDP) values were also discarded because of high within-tree and within-log variability. This affected the absolute number of boards in the optimum grade. Overall, pre-sorting at the tree level was found to be less efficient in increasing the C16 board proportion. In order to reach the current C16 yield for mature

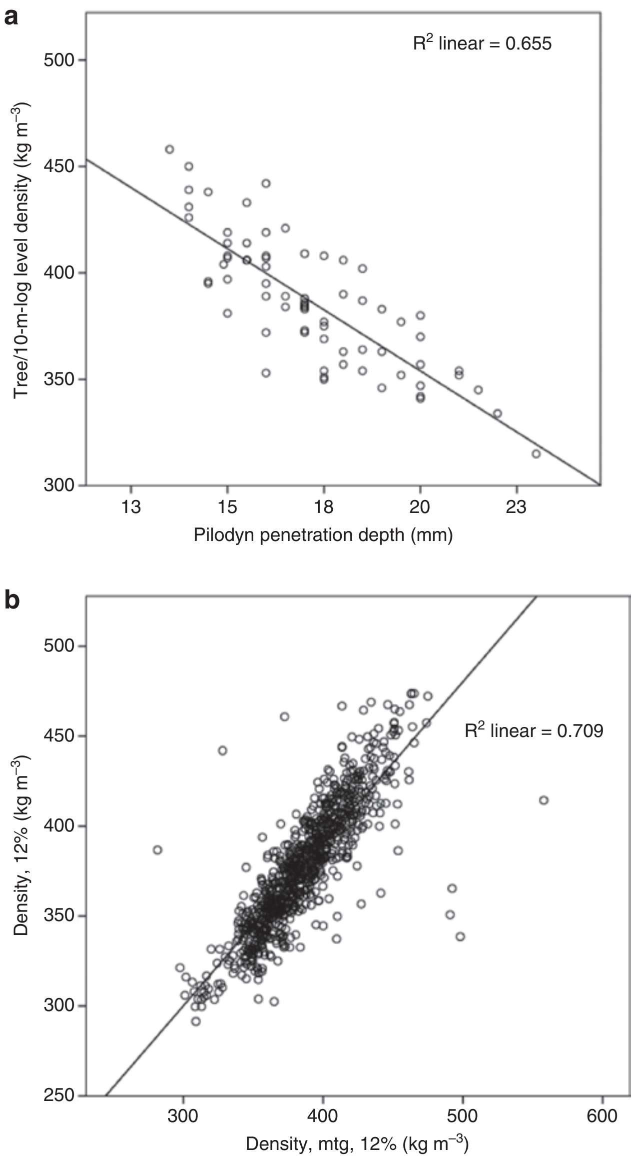

Figure 4: (a) Relationships between Pilodyn penetration and mean density of sawn timber and (b) between density measured on full size boards by the MTG method and density on small specimens in accordance with EN 408.

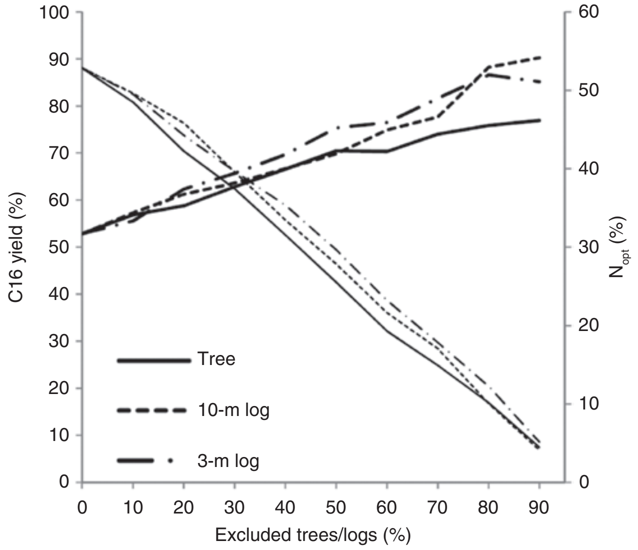

Figure 5: Effects of tree and log pre-sorting on C16 yield (thick lines) and absolute proportion of C16 optimum grade boards (N_{opt}) (thin lines).

Irish grown Sitka spruce timber (≥90%), ca. 80% of the logs were excluded in the pre-sorting. After this exclusion, the proportions of C16 optimum grade boards were 10% and 12% of the total number of boards without pre-sorting (N_{opt}) for 10-m logs and 3-m logs, respectively. At the tree level, a C16 yield of ca. 80% is achieved when 90% of the trees were excluded. It is important to note that results presented for pre-sorting are based on the optimum grade and that lower yields can be expected in practice.

The results show very high VA in the grade-determining properties of the 23-year-old Sitka spruce timber, which could be considered as representative of a thinning material. The ability of NDTs to predict data has been quantified. At the tree level, the SWV explained 41% VA in avgMOE. An improved model that included a combination of SWV and PD (tree MOE_{dyn}) explained an additional 14% VA in avgMOE. However, due to high within-a-tree VA in timber MOE, tree MOE_{dyn} accounted only for 18% VA in MOE at the board level. This is in line with other studies. Brüchert et al. (2011) reported that the SWV of Scots pine and Norway spruce trees in Germany and Sweden explained 26.6% VA in MOE_{dyn} of an individual board. In Norway, Fischer et al. (2015) found that SWV measured on Norway spruce trees accounted for 12.7% VA in board data measured using a strength grading machine.

PD was a better predictor of BStr ($R^2=0.31$) than SWV ($R^2=0.27$), although the difference was small. The combination of SWV and PD explained more VA ($R^2=0.47$) in avgBStr than the individual measurements. PD was the best predictor of timber D ($R^2=0.66$). Interestingly, PD and SWV combination weakened the results ($R^2=0.53$).

At the 3-m-log level, the MOE_{dyn} explained an additional 16% VA in avgMOE compared to the 3-m-log fundamental frequency alone. The 3-m-log MOE_{dyn} explained 50% VA in avgMOE of timber boards and 24% VA in MOE at an individual board level. The differences between the explained variance in avgMOE and individual values are due to the large VA in board MOE within a log. This is similar to the findings by Tsehaye et al. (2000), who reported that SWV measured on 4.2-m radiata pine logs explained 46% VA in avgMOE measured on boards, while butt logs showed the strongest relationship with board MOE, which is in agreement with the findings in the present study. Rais et al. (2013) found that SWV of 4.1-m Douglas fir logs explained 71% VA in avgMOE$_{dyn}$ of dry boards and 45% VA in MOE$_{dyn}$ of individual boards. However, the results in the quoted study are higher than the literature data. Fischer et al. (2015) presented a model for Norway spruce, in which acoustic velocity at a log level explained 43% VA in board MOE$_{dyn}$. In the UK, the MOE$_{dyn}$ of Sitka spruce logs accounted for 45% VA in sawn timber MOE (Moore et al. 2013). The quoted authors set the timber D arbitrarily to 1000 kg m^{-3} for the log MOE$_{dyn}$ calculations. In the current study, the D$_{green}$ was 16% lower than that on average and ranged from 732 to 919 kg m^{-3}. This is consistent with the findings on British-grown Sitka spruce, where D$_{green}$ had an average of 850 kg m^{-3} (Moore 2011). The D$_{green}$ of 3-m logs explained more VA in avgBStr and avgD of boards than the fundamental frequency. There are arguments that the integration of D data in forest practice is difficult, but nowadays D can be obtained from harvesting machines during the tree felling process.

The findings of this study concerning MOE prediction are consistent with those of other studies, but grade-determining properties are not available in the literature. The current study shows that for young Sitka spruce with a high juvenile wood content, the MOE$_{dyn}$ at the tree and 10-m-log level predicted ca. 50% of the avgBStr and avgD. At the 3-m-log level, the relationship was significantly weaker.

The MOE$_{dyn}$ of 10-m logs ($E_{dyn,10m\ log}$) showed the strongest relationship with avgMOE of sawn timber ($R^2 = 0.66$). Rais et al. (2013) found a very strong relationship ($R^2 = 0.94$) between MOE$_{dyn}$ of 13-m logs and avgMOE$_{dyn}$ of 4.1-m Douglas fir. It seems that measurements on long or short logs have almost the same predictive capability in terms of MOE. In principle, this is consistent with the findings presented here for MOE, but at the 3-m-log level, the MOE$_{dyn}$ explained a significantly less VA in BStr and D than at the 10-m-log level. Accordingly, the log position along the stem affects the relationships between the MOE$_{dyn}$ and BStr and D.

The results at the board level showed a dependency of acoustic measurements by the MTG instrument on the board cross-section size. The MOE$_{dyn}$ had a weaker relationship with the MOE obtained by a four-point-bending test for 35 mm × 75 mm boards than for 44 mm × 100 mm boards. One possible explanation is that the hammer and accelerometer of the MTG instrument were too close to the edge of a board during the measurements on the smaller boards for optimum performance, although this cross-section is still within the permitted size range of the instrument (CEN 2009).

Llana et al. (2018a) found linear relationships between SWV obtained using five different devices on four pine species and MC measured on timber boards. The relationships were different above or below FSP, but the prediction of timber properties was not affected by MC. Rais et al. (2013) found a very strong relationship between the MOE$_{dyn}$ of wet and dry boards ($R^2 = 0.94$), consistent with the findings in the present study. In summary, acoustic tools are well suitable to assess wood properties based on values derived from wet boards. The rejected boards could be eliminated and the kiln drying costs be reduced. The dried timber can be checked for fissures and distortion and still be considered as dry-graded (Ridley-Ellis et al. 2016).

The modelling of pre-sorting of young Sitka spruce trees and logs was undertaken to explore the possibilities of acoustic tools for segregating higher and lower quality materials from early thinnings, which could meet the C16 yield of mature Irish timber. The main purpose of the models was to identify measurement tools and levels on which prediction of sawn timber properties is more efficient. A higher proportion of the resulting boards would meet the C16 grade if pre-sorting is done at the log level than at the tree level. Pre-sorting at the log level showed higher yields of C16 strength class than pre-sorting at the tree level. Pre-grading based on standing trees did not improve the current C16 yields for Irish grown Sitka spruce timber (≥90%). This lack of efficiency can be explained by the relatively short distance covered by the TOF measurement on a standing tree. Rais et al. (2013) concluded that pre-grading by SWV measurements on Douglas fir standing trees was not efficient and that these data are only a rough guide for timber quality assessment, and that log level pre-grading is more efficient. The results of the present study also showed that pre-sorting at the log level is more effective in reaching the current C16 yields of Irish timber.

Conclusions

This study has demonstrated that acoustic measurements are effective for pre-sorting of young timber material with high juvenile wood content and the results are consistent with the findings in the literature. The combination of acoustic and D measurements on young Sitka spruce trees is useful to select material with higher MOE, BStr and D. The quantity of Sitka spruce structural timber available to the market can be increased by the selection of trees and logs from early thinnings with the desired quality based on MOE$_{dyn}$ measurement, although higher efficiency can be achieved at the log level. The models presented here may also be useful for tree breeders and geneticists working on timber quality improvement studies. But of course, the available database should be expanded with materials collected from different geographic locations and age groups.

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