Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/forestsystems
http://dx.doi.org/10.5424/fs/2014231-04706

Forest Systems 2014 23(1): 153-166
ISSN: 2171-5068
eISSN: 2171-9845

Modelling modulus of elasticity of *Pinus pinaster* Ait. in northwestern Spain with standing tree acoustic measurements, tree, stand and site variables

Esther Merlo[1]*, Juan Gabriel Alvarez-Gonzalez[2], Oscar Santaclara[1]
and Guillermo Riesco[2]

*[1] Madera Plus Calidad Forestal, S.L. Parque Tecnológico de Galicia. Rúa de Vigo, 2.
32900 San Cibrao das Viñas (Ourense), Spain. [2] Departamento de Ingeniería Agroforestal.
Unidad de Gestión Forestal Sostenible. Universidad de Santiago de Compostela. Escola Politécnica Superior.
Campus Universitario, s/n. 27002 Lugo, Spain*

Abstract

Aim of study: Modelling the structural quality of *Pinus pinaster* Ait. wood on the basis of measurements made on standing trees is essential because of the importance of the species in the Galician forestry and timber industries and the good mechanical properties of its wood. In this study, we investigated how timber stiffness is affected by tree and stand properties, climatic and edaphic characteristics and competition.

Area of study: The study was performed in Galicia, north-western Spain.

Material and methods: Ten pure and even-aged *P. pinaster* stands were selected and tree and stand variables and the stress wave velocity of 410 standing trees were measured. A sub-sample of 73 trees, representing the variability in acoustic velocity, were felled and sawed into structural timber pieces (224) which were subjected to a bending test to determine the modulus of elasticity (MOE).

Main results: Linear models including wood properties explained more than 97%, 73% and 60% of the observed MOE variability at site, tree and board level, respectively, with acoustic velocity and wood density as the main regressors. Other linear models, which did not include wood density, explained more than 88%, 69% and 55% of the observed MOE variability at site, tree and board level, respectively, with acoustic velocity as the main regressor. Moreover, a classification tree for estimating the visual grade according to standard UNE 56544:2011 was developed.

Research highlights: The results have demonstrated the usefulness of acoustic velocity for predicting MOE in standing trees. The use of the fitted equations together with existing dynamic growth models will enable preliminary assessment of timber stiffness in relation to different silvicultural alternatives used with this species.

Key words: stress wave velocity; modulus of elasticity; site index; competition index; stepwise regression; CART.

Introduction

Pinus pinaster Ait. is one of the most important coniferous species used in the timber industry in Spain, especially in Galicia (NW Spain) where it covers around 587,000 ha of land and is the main forest industry resource. More than 2.8 million cubic meters of *Pinus pinaster* round wood are produced annually in Galicia, representing 72% of the total production of the species in Spain. Recent studies have demonstrated the good mechanical properties of Galician *P. pinaster* timber, which make it suitable for structural use (Riesco and Díaz González, 2007; Carballo *et al.*, 2009).

Forest management and climatic and soil factors have important effects on softwood properties (*e.g.* Lasserre *et al.*, 2004; 2008; Moore *et al.*, 2009; 2013; Roth *et al.*, 2007; Watt *et al.*, 2006; 2008). Studies carried out in different regions have assessed the influence of these factors on the variation in wood properties in coniferous species (*e.g.* Lei *et al.*, 2005; Liu *et al.*, 2007, or Ikonen *et al.*, 2008). The use of portable acoustic devices that estimate timber stiffness from measurements made on standing trees (*e.g.* Wang *et al.*, 2001b; 2007; Merlo *et al.*, 2008, 2009; Santaclara *et al.*, 2011) is a key element of these studies. Stiffness (quantified by the modulus of elasticity, MOE) is an important mechanical property of timber and it is commonly measured in machine grading of timber strength. It is also the index parameter considered by

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* Corresponding author: maderaplus@maderaplus.es
Received: 05-07-13. Accepted: 28-11-13.

engineers in designing structures for the serviceability limit state under Eurocode 5 (AENOR, 2006). A good relationship between standing tree acoustic measurements and wood properties of the trees would enable the use of acoustic tools to assess the value of timber as structural material. This information would enable the wood processing sector to optimize resources and future investments with the aim of increasing industrial efficiency. The data would enable identification of the proportion of the trees in the stand that could be used for construction. It would also enable identification of those stands of poor structural quality, which could then be managed for other more appropriate purposes.

Determination of the factors that affect stiffness is critical, as this information can be used to develop models that provide predictions about this property across broad environmental gradients. Models that predict MOE on the basis of tree and site variables could be integrated with models describing how silviculture and site characteristics influence this property. This would enable managers to design site-specific silviculture practices to optimise the end-product value.

The aims of this study were to analyze how timber stiffness is influenced by tree, stand and competition characteristics and to propose a model based on acoustic data from standing trees. This would provide a reliable and non-destructive method of predicting the elastic properties of *P. pinaster* wood.

Material and methods

Site description and measurements

The material used in this study was collected from 10 pure mature even-aged *Pinus pinaster* stands located throughout the distribution area of the species in Galicia with ages ranged from 43 to 65 years. With the aim of examining the influence of site factors on wood properties, the stands were subjectively selected to cover the range of site productivity, quantified by site index. Conventional management of maritime pine in Northwestern Spain to yield 300-400 crop trees per hectare at the rotation age was applied to all of the stands.

A rectangular 0.05-ha sample plot (25 × 20 m) was installed in each stand. The following variables were measured for each tree within the plots: X and Y coordinates (m), total height (H, m), diameter at breast height (DBH, cm), average crown width (CW, m) and crown length (CL, m). Stem slenderness and crown ratio were defined as H/DBH and CL/H, respectively. The stand variables basal area (G), number of stems per hectare (N), mean height ($\bar{h}$), dominant height (H_0) defined as the mean height of the 100 thickest trees per hectare, and site index at a reference age of 20 years were also calculated for each plot, using the equation proposed by Álvarez González *et al*. (2005). Other tree attributes, such as the presence of forks, broken or defective tops, external resin bleeding, severe lean and other type of malformations, were also recorded.

The stress wave velocity was measured in each stem by using the IML Electronic Hammer (Instrumenta Mechanic Labor GmbH, Germany). The probes were modified to be hammered into trees, allowing penetrating through the bark on the wood. In some cases it was also necessary to remove the bark of the tree before the measure. One measurement was made at each of the four cardinal points on each stem. At each point, measurements were taken until the differences between three consecutive values were less than 100 m/s, and the average value of the three measurements was recorded (Moore *et al*., 2009). The stress wave velocity of the tree was calculated as the mean value of the four cardinal measurements.

Chemical and physical properties of soil and litter layer were measured in each sample plot. Sub-samples of the mineral soil layer were collected with a steel corer, at 5 points in each sample plot, and were combined to form one bulk sample per plot. These samples were oven-dried at 40°C and sieved at 2 mm for determination of the stoniness. Total C and N in the fine soil fraction were analyzed with a LECO Elemental analyzer. Available P, Ca, Mg, K, Mn, Fe, Cu, Ni, Al and Zn were extracted by the Mehlich 3 procedure (Mehlich, 1984) and were determined by ICP-OES.

At each sampling point, five density cores were collected in a 100 cm^3 metal cylinder. The cores were oven-dried at 105°C and weighed to determine the bulk density, following the methodology of Blake and Hartge (1986). The pH was measured in water, with a glass electrode.

To sample the litter layer, 0.3 × 0.3 m square frames were thrown at random within each plot, on 5 occasions. All aboveground soil litter was collected and dried at 40°C to constant weight. The samples were analyzed for pH in water, total C, total N and available macro- and micro-nutrients, using the above-described methods.

Monthly precipitation and mean, maximum and minimum monthly temperatures in each sample plot were obtained from a grid of meteorological stations distributed throughout Galicia, by using the spatial

Table 1. Summary statistics of the site level variation in soil and litter properties and climatic variables

Variable	Mean	Std. Dev.	Maximum	Minimum
Soil properties				
Carbon (%)	7.02	1.78	8.87	4.15
Nitrogen (%)	0.39	0.12	0.56	0.21
pH	4.48	0.43	4.96	3.79
Olsen P (mg/kg)	6.13	1.54	8.28	3.80
Exch. K (mg/kg)	73.93	18.77	96.39	45.84
Exch. Mg (mg/kg)	33.52	12.43	48.69	15.99
Exch. Mn (mg/kg)	27.52	27.49	68.31	1.37
Exch. Ca (mg/kg)	29.39	16.26	54.12	11.14
Exch. Fe (mg/kg)	268.33	84.45	398.06	146.32
Exch. Al (mg/kg)	2,066.02	221.94	2,312.54	1,642.13
Soil organic matter (%)	12.10	3.06	15.28	7.16
Litter chemical properties				
Carbon (%)	44.15	6.41	49.30	31.77
Nitrogen (%)	1.10	0.33	1.65	0.62
Olsen P (mg/g)	0.50	0.12	0.68	0.31
N/P	21.75	4.24	29.59	16.29
Exch. K (mg/g)	0.73	0.42	1.77	0.41
Exch. Mg (mg/g)	1.19	0.41	2.01	0.73
Exch. Mn (mg/g)	0.40	0.42	1.31	0.03
Exch. Ca (mg/g)	2.17	0.62	2.69	1.06
Exch. Fe (mg/g)	3.15	3.69	10.96	0.43
Exch. Al (mg/g)	2.53	2.92	9.68	0.54
Climatic variables				
Mean annual air temperature (°C)	12.57	1.84	14.80	9.46
Mean minimum annual air temperature (°C)	7.66	1.58	9.92	5.17
Mean minimum autumn air temperature (°C)	11.31	2.28	15.31	7.36
Annual rainfall (mm)	1,332.69	474.26	2,350.48	738.00
Summer rainfall (mm)	208.61	59.78	327.61	136.40

interpolation proposed by Rodríguez Guitián (2004). The main soil and litter properties and climatic variables are shown in Table 1.

Lumber processing and wood properties evaluation

A sub-sample of 5-10 well-formed trees per sample plot, of diameter at breast height between 25 and 45 cm, was selected to cover the complete range of stress wave velocities observed in each plot from a total of 410 standing trees evaluated. A total of 73 sample trees were felled and the first 8 meters from the butt were bucked into two logs of 3 and 5 meters. Each log was labelled, the diameter and bark thickness were measured at both ends, and the log position in the tree was recorded. A 10-cm-thick disk was removed at the base of the stem. All the logs were processed in the same way from debarking to sawing. The logs were debarked and then sawn into structural timber pieces of 200 × 200 × 5,000 mm, 200 × 150 × 5,000 mm, 150 × 100 × 3,000 mm and 150 × 50 × 3,000 mm, depending on log dimensions and log defects. A total of 224 structural pieces were finally obtained (43 of 200 × 200 × 5,000 mm, 38 of 200 × 150 × 5,000 mm, 40 of 150 × 100 × 3,000 mm and 103 of 150 × 50 × 3,000 mm). Each piece was identified by tree number and log position. All pieces were air-dried until the timber reached an equilibrium moisture content of roughly 12%. The modulus of elasticity in bending (MOE) of the timber was determined by the edgewise four-point static bending test, as established by standard UNE-EN 408:2011 (AENOR, 2012). The modulus of elasticity of a specific tree (MOE_{tree}) was calculated as the mean value of the modulus of elasticity of the timber pieces obtained in this tree (MOE_{board}). The modulus of elasticity of each site (MOE_{site}) was calculated as the weighted mean value of the MOE_{tree} using the number of pieces of each tree as weight.

Each piece was visually graded according to standard UNE 56544:2011 (AENOR, 2011). This standard classifies structural timber on the basis of its defects and dimensions. Grade MEG was applied to structurally-apt material thicker than 70 mm (only pieces of 200 × 200 × 5,000 mm, 200 × 150 × 5,000 mm and 150 × 100 × 3,000 mm were considered) while grades ME-1 or ME-2 were applied to structurally-apt pieces thinner than 70 mm (150 × 50 × 3,000 mm); pieces not apt for structural use were classified as "excluded".

For wood density analysis, a rectangular piece of 5x2 mm (a radial segment from pith to bark) was cut from each 10-cm-thick disk. Radial wood samples were dried to equilibrium moisture of 12%, and resins were extracted with a solution of ethanol. A radial X-ray density profile was obtained from each sample by the indirect-reading X-ray densitometry method described by Polge (1966) and adapted by Mothe *et al.* (1998) and Rozenberg (2001). The following parameters were determined in each ring: ring width (mm); earlywood and latewood widths (mm); mean, maximum and minimum wood density (g/cm^3) and earlywood and latewood densities (g/cm^3). The mean wood density (WD) and the latewood width proportion (LWW) were calculated for each radial segment, using the ring variables described. The EW-LW boundary in each growth ring was determined according to the model proposed by Rozenberg (2001). Analysis of the variations in mean wood density from pith to bark of all the sample trees revealed the presence of juvenile wood, at least in the first 10 rings from the pith. This threshold was therefore used to calculate juvenile wood ring width (mm) and juvenile wood density (g/cm^3).

Competition indices

To analyse the effect of competition on wood properties, 7 different competition indices were calculated for each of the 73 sample trees (Table 2). The first

Table 2. Competition indices and corresponding equations tested to analyze the influence of competition on wood properties

Competition index	Equation
Basal area of larger trees (BAL) Wykoff *et al.* (1982)	$\sum_{j=1}^{t} \frac{\pi \cdot DBH_j^2}{4} \quad DBH_j \geq DBH_i$
BAL relative	$\frac{BAL_i}{g_{plot}}$
Hegyi (1974)	$\sum_{i \neq j} \frac{DBH_j}{DBH_i \cdot Dist_{ij}}$
Martin and Ek (1984)	$\sum_{i \neq j} \frac{DBH_j}{DBH_i} \cdot \exp\left(\frac{16 \cdot Dist_{ij}}{DBH_i + DBH_j}\right)$
Daniels *et al.* (1986)	$\frac{DBH_i^2 \cdot n}{\sum DBH_j^2}$
Pukkala and Kolström (1987)	$\sum_{i \neq j} \frac{H_i}{H_j \cdot Dist_{ij}}$
Crown cross-sectional area (CCS)	$\sum_{i \neq j} \frac{CC_j}{CC_i \cdot Dist_{ij}}$

where DBH_i and DBH_j are the diameter at breast height of the sample tree and the competitor tree, respectively (m); g_{plot} is the basal area of the sample plot (m^2); $Dist_{ij}$ is the distance between competitor and sample tree (m); n is the number of competitors; H_i and H_j are the total height of sample and competitor tree, respectively (m) and CC_i and CC_j are the crown cross-sectional-area of sample and competitor tree, respectively, evaluated at 66% of the crown height from the top (m^2) of the sample tree.

two are distance-independent indices, and all trees in each sample plot were considered as possible competitors of the sample tree. The value of the other five competition indices depends on the method used to define neighbouring trees as competitors. In this study, four competitors were considered for each sample tree and each was defined as the nearest tree inside each quadrant delimited by the cardinal points from the sample tree.

The mean, maximum and minimum values and the standard deviation of the main stand and tree variables, the calculated values of the competition indices and wood properties are listed in Table 3.

Table 3. Summary statistics of the main stand and tree variables, including the values of the competition indices used in the study and the main wood properties

Variable	Mean	Std. Dev.	Maximum	Miminum
Stand variables				
Stems per ha	467.71	175.64	726.60	287.98
Basal area (m^2/ha)	51.48	9.88	69.14	37.37
Mean height (m)	21.58	2.05	23.64	18.23
Dominant height (m)	22.89	2.16	25.43	19.59
Site index (m)	12.74	1.61	14.99	9.49
Age (years)	52.00	7.52	65.00	43.00
Tree variables				
DBH (cm)	42.47	5.46	58.45	21.40
Total height (m)	22.88	2.44	27.50	17.30
Stem slenderness	0.55	0.09	0.72	0.35
Crown length (m)	16.10	2.60	20.60	10.60
Crown ratio	0.70	0.07	0.86	0.53
Competition indices				
BAL (m^2/ha)	43.96	23.29	114.54	5.18
BAL relative	0.55	0.22	1.00	0.06
Hegyi (1974)	0.77	0.23	1.54	0.40
Martin and Ek (1984)	43.39	162.80	907.92	4.60
Daniels *et al.* (1986)	1.23	0.48	2.43	0.57
Pukkala and Kolström (1987)	0.89	0.26	1.72	0.46
Crown cross-sectional area (CCS)	0.78	0.34	2.26	0.30
Wood properties				
MOE (GPa)	11.04	3.77	25.29	4.04
Stress wave velocity (m/s)	2,985.00	3,03.03	4,316.00	2,461.00
Ring width (mm)	3.04	0.79	5.73	1.67
Earlywood width (mm)	2.10	0.54	4.01	1.06
Latewood width (mm)	0.94	0.29	1.72	0.61
Latewood width proportion	0.29	0.05	0.35	0.21
Wood density (g/cm^3)	0.49	0.05	0.61	0.39
Earlywood density (g/cm^3)	0.43	0.04	0.53	0.34
Latewood density (g/cm^3)	0.70	0.06	0.85	0.56
Juvenile wood ring width (mm)	5.14	1.11	7.33	3.55
Juvenile wood density (g/cm^3)	0.49	0.04	0.55	0.45

Modelling methods

A random-effect model was used to estimate the percentage of total variation in MOE$_{board}$ attributable to each stratum (stand, tree and log). A nested structure was assumed for the random effects of tree and site following the model:

$$y_{ijkl} = \mu + S_i + T_{j(i)} + L_{k(ij)} + e_{l(kij)} \qquad [1]$$

where y_{ijkl} is the MOE$_{board}$ on an individual piece of timber, μ is the overall mean, S_i is the random effect of the ith site [~N(0, σ_S^2)], $T_{j(i)}$ is the random effect of the jth tree within the ith site [~N(0, σ_T^2)], $L_{k(ij)}$ is the random effect of the kth log within the jth tree [~N(0, σ_L^2)], and $e_{l(ijk)}$ is the random effect of the lth piece of timber from the kth log [~N(0, σ_e^2)].

Linear models relating the MOE$_{site}$, MOE$_{tree}$ and MOE$_{board}$ values to the measured tree and stand variables, soil characteristics, climatic variables and other wood properties were developed. Selection of the best set of independent variables was carried out by applying the stepwise variable selection method, combined with preliminary graphical and correlation analyse of the data and an understanding of the fitting process.

To evaluate the presence of multicollinearity among variables in the models analyzed, the variance inflation factors (*VIF*) of all the independent variables was calculated as follows:

$$VIF = \frac{1}{1 - R_i^2} \qquad [2]$$

where R^2_i is the multiple correlation coefficient obtained when the ith independent variable X_i is regressed against all the remaining independent variables in the model. Values up to 10 were accepted, in accordance with Der and Everitt (2002).

Evaluation of the model performance was based on graphical analysis, by plotting the observed against predicted values of the dependent variable, and the studentized residuals against the estimated values residuals and two statistical indices: the root-mean-square error (*RMSE*), which analyzes the precision of the estimates; and the adjusted coefficient of determination ($R^2_{adj.}$), which reflects the part of the total variance that is explained by the model and which takes into account the number of parameters that it is necessary to estimate. These statistics are expressed as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{n - p}} \qquad [3]$$

$$R^2_{adj.} = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad [4]$$

where y_i $\hat{y}_i$, and y are the observed, predicted and mean values of the dependent variable, respectively, n the total number of observations, and p the number of parameters in the model.

Finally, a cross-validation approach was used to evaluate the predictive capability of the models. The adjusted model efficiency for the estimates (MEF_{adj}), calculated by equation [4], was estimated by using the residual of each MOE observation, which was obtained by refitting the model without this observation residual. Also, plots of the studentized residuals against the predicted MOE and plots showing the observed against the predicted MOE in cross-validation were analysed to search for systematic trends. All analyses were undertaken in SAS (SAS Institute Inc., 2004).

Visual grading classification

A classification tree was used to relate the visual grades (defined as MEG, ME-1, ME-2 and excluded) to the measured tree and stand variables. Classification tree analysis is a non-parametric technique for the sequential partitioning of a data set composed of a categorical response variable and any number of potential continuous or categorical predictor variables, by use of dichotomous criteria (Breiman *et al.*, 1984). After each split, the technique searches for the predictor variable that provides the most effective binary separation of the range in the response variable. As a result, predictor variables can be used more than once.

The classification tree analysis was performed using the *rpart* package from R (R Development Core Team, 2011; Therneau and Atkinson, 2012). This approach sequentially partitions the data set, on the basis of predictor variables, into the most pure class memberships possible. Instead of applying stopping rules, it generates a sequence of sub-trees by growing a large tree and pruning it back until only the root node is left. Cross-validation is then used to estimate the misclassification cost of each sub-tree by determining the number of correct and incorrect classifications, and the sub-tree with the lowest estimated cost is chosen.

Results

Effect of site and stand variables on mean sample plot MOE$_{site}$

The Pearson correlation coefficients between the MOE$_{site}$ and climatic and edaphic variables were also calculated. Only four variables were significantly related to MOE$_{site}$: the soil litter nitrogen (N) fraction ($r = –0.7503$, $p = 0.0199$); the soil litter N/P ratio ($r = –0.8828$, $p = 0.0016$); the mean annual temperature ($r = 0.9231$, $p = 0.0030$) and the mean minimum annual temperature ($r = 0.7212$, $p = 0.0283$).

The MOE$_{site}$ was also strongly correlated with some stand variables. Specifically, the MOE$_{site}$ was significantly and positively related to mean height ($r = 0.6722$, $p = 0.0473$) and site index ($r = 0.6845$, $p = 0.0420$), whereas MOE$_{site}$ was significantly and negatively related to basal area ($r = –0.7005$, $p = 0.0356$). The number of stems per hectare ($p = 0.7381$) and stand age ($p = 0.5668$) were not significantly correlated with MOE$_{site}$.

Significant and positive correlations were also found between MOE$_{site}$ and mean density ($r = 0.8838$, $p = 0.0016$) and mean stress wave velocity ($r = 0.7586$, $p = 0.0178$).

Effect of site, stand and tree variables on mean tree MOE$_{tree}$ and MOE$_{board}$

In total, 20 site, tree and stand variables were significantly correlated with MOE$_{tree}$ (Table 4). As expected from the results obtained for the sample plot the mean annual temperature, mean minimum annual temperature, mean height, dominant height and site index were significantly and positively correlated with MOE$_{tree}$, while the soil litter nitrogen fraction, soil litter N/P ratio, and basal area were significantly and negatively correlated with this parameter. The stand age ($p = 0.2064$) and number of stems per hectare ($p = 0.8382$) were not significantly correlated with MOE$_{tree}$.

The tree variables most strongly correlated with MOE$_{tree}$ were stem slenderness (positive), and DBH and crown ratio (negative). As regards the competition indices used, only the basal area of largest trees (BAL) and the index proposed by Daniels *et al.* (1986) were significantly (although only just), linearly correlated with MOE$_{tree}$, indicating a reduction in this parameter when tree competition increases.

Table 4. Site, tree and stand variables that were significantly correlated with MOE. The Pearson's correlation coefficient and the significance level are shown for each variable

Variable	Sampled trees	Correlation coefficient (*r*)	Prob> |*r*| under H0: $r = 0$
Site variables			
Litter N%	73	–0.6037	< 0.0001
Litter N/P	73	–0.6679	< 0.0001
Mean annual temperature (°C)	73	0.7212	< 0.0001
Mean minimum annual temp. (°C)	73	0.4589	<0.0001
Stand variables			
Basal area (m^2/ha)	73	–0.6637	< 0.0001
Mean height (m)	73	0.5949	< 0.0001
Dominant height (m)	73	0.5220	< 0.0001
Site index (m)	73	0.5721	< 0.0001
Tree variables			
DBH (cm)	73	–0.4489	< 0.0001
Total height (m)	73	0.4996	< 0.0001
Stem slenderness	73	0.6060	< 0.0001
Crown ratio	73	–0.4173	0.0002
Competition indices			
BAL	73	–0.3326	0.0040
Daniels *et al.* (1986)	73	–0.2462	0.0358
Wood properties			
Stress wave velocity (m/s)	73	0.6408	< 0.0001
Latewood width proportion	73	0.6319	< 0.0001
Wood density (g/cm^3)	73	0.7340	< 0.0001
Earlywood density (g/cm^3)	73	0.4839	< 0.0001
Latewood density (g/cm^3)	73	0.5673	< 0.0001
Juvenile wood density (g/cm^3)	73	0.5961	< 0.0001

As expected, the mean density was the wood property most closely correlated with MOE_{tree} ($r = 0.7340$, $p < 0.0001$), although strong and positive relationships between MOE_{tree} and latewood width proportion ($r = 0.6319$, $p < 0.0001$) and all of the within-ring density parameters based on the earlywood-latewood boundary were also found.

The significant and positive correlation between stress wave velocity and MOE_{tree} confirmed the previously reported potential of acoustic technology as a good estimator of the mechanical properties of wood in standing trees (*e.g.* Wang *et al.*, 2001b; Carter *et al.*, 2005; Ishiguri *et al.*, 2008).

Regarding the values of the modulus of elasticity at board level (MOE_{board}), the same 20 site, stand and tree variables showed significant correlations.

Models to estimate modulus of elasticity MOE_{site}, MOE_{tree} and MOE_{board}

The results of the random-effects model indicated that of the overall variation in MOE_{board}, the 52.65% was attributed to differences between sites, the 28.01% to differences between trees within a site, the 5.63% to differences between logs within a tree and the 13.71% to differences between pieces within a log.

Two different linear models to estimate MOE_{site}, MOE_{tree} and MOE_{board} from site, tree and stand characteristics were fitted. Firstly, linear models including all the variables previously showed to be significantly correlated with MOE_{site}, MOE_{tree} and MOE_{board} were fitted. The stepwise variable selection method, together with an understanding of the process modelled, was used to select the best set of independent variables. The values of the variance inflation factor (VIF) were analysed to prevent multicollinearity. To analyse the effect of log position on MOE_{board}, a dummy variable with a value of 1 for the 1st log and 0 for the 2nd log was included as an independent variable. The parameter estimates and the goodness of fit statistics of models 1, 3 and 5 for MOE_{site}, MOE_{tree} and MOE_{board}, respectively are shown in Table 5.

All the parameters were significant at the 0.05 probability level; the values of VIF did not indicate any problem of collinearity, and the values and signs of the parameters were biologically consistent. At site level, modulus of elasticity was related to stress wave velocity, wood density and site index (model 1). This model explained almost the 98% of the total variability observed. MOE_{tree} was best predicted by wood density, stress wave velocity, dominant height and soil litter N/P ratio (model 3). This model explained 73.73% of the total variance in modulus of elasticity with a value of the adjusted model efficiency of the estimates (MEF_{adj}) of 68.01%. At board level, the best set of independent variables included wood density, stress wave velocity, total height, dominant height and soil litter N/P ratio (model 5), explaining the 60.33% of the total variability in MOE_{board}. The parameter associated with the log position was not significant at the 5% level and therefore, model 5 was refitted without this variable. Plots of studentized residuals of the three models provided random patterns around zero, with homogeneous variance and no detectable significant trends.

As the objective of the study was to obtain models for estimating MOE that are easy to use from a prac-

Table 5. Summary of model statistics and coefficient values for the multiple linear regression model of MOE including structural wood variables

Equation form and parameter estimates	R^2_{adj}	RMSE	MEF$_{adj}$
Stand-level equations (n = 10)			
(Model 1) $MOE_{site} = -21.9739 + 0.0023SWV + 36.8856WD + 0.6723SI$	0.9791	2.0876	0.9338
(Model 2) $MOE_{site} = -21.1544 + 0.0075SWV + 0.7820SI$	0.8853	4.5458	0.7801
Tree-level equations (n = 73)			
(Model 3) $MOE_{tree} = -13.5834 + 0.0038SWV + 17.04105WD + 0.4067H_0 - 0.1856N/P$	0.7373	3.0507	0.6801
(Model 4) $MOE_{tree} = 0.0047SWV - 6.0740BAL - 0.1056G + 0.5097SI - 0.0776DBH$	0.6921	3.1634	0.6195
Board-level equations (n = 224)			
(Model 5) $MOE_{board} = -14.1119 + 0.0035SWV + 18.5879WD + 0.1992H - 0.1777N/P + 0.2268H_0$	0.6033	2.3719	0.5709
(Model 6) $MOE_{board} = 0.0045SWV - 0.57942BAL - 0.0865G + 0.3746H_0 - 0.1259DBH$	0.5512	2.5229	0.5142

N/P: soil litter Nitrogenous-Phosphorus ratio. SI: site index, defined as the dominant height (m) at a reference age of 20 years. SWV: stress wave velocity (m/s). WD: wood density (g/cm^3). H_0: dominant height (m). BAL is the basal area of largest trees (m^2/ha). G: stand basal area (m^2/ha). DBH: diameter at breast height (cm). H: total height of the tree (m).

tical point of view, in a second step, linear models without including independent variables difficult to measure (wood properties and soil and climatic variables) were fitted. The dummy variable for log position was included in model 6. The results of models 2, 4 and 6 for MOE$_{site}$, MOE$_{tree}$ and MOE$_{board}$, respectively are shown in Table 5.

All of the parameters were again found to be significant at the 5% significance level, except for the intercept in models 4 and 6. Therefore, these models were refitted without an intercept. The new models showed biologically consistent values and signs, and the VIF values did not indicate any problems of multicollinearity. At site level, modulus of elasticity was best predicted by stress wave velocity (SWV) and site index (SI). Model 2 explained the 88.53% of the observed variability. The best set of independent variables for MOE$_{tree}$ (model 4) included stress wave velocity, DBH, basal area of larger trees (BAL), stand basal area (G) and site index (SI). At board level, the parameter associated with the log position was not significant and, therefore, model 6 was refitted without this variable. Finally, the best set of independent variables for model 6 included the same variables that MOE$_{tree}$ (model 4) and the total height of the tree. All the independent variables included in model 4 and 6 are easy to measure in a forest inventory. The scatter plots of observed modulus of elasticity values (GPa) against predicted modulus of elasticity obtained with models 3 and 4 at tree level and 5 and 6 at board level are shown in Fig. 1.

Visual grading

The application of standard UNE 56544:2011 (AENOR, 2011) to visual grading resulted in a 83.47% of the pieces thicker than 70 mm (121 pieces) being classified as structurally-apt materials (“MEG”), while 27.91% of pieces thinner than 70 mm (103 pieces) were classified as structurally-apt materials of the top grade (“ME-1”) and 48.84% of these pieces were assigned to the second grade (“ME-2”). The classification tree obtained is shown in Fig. 2.

Discussion

Effect of site and stand variables on mean sample plot MOE$_{site}$

The strong negative correlation between the soil litter N/P ratio and MOE$_{site}$ may be due to the influence of phosphorus (P) assimilation on frost tolerance. A high concentration of P in the soil litter (low N/P ratio) may increase frost tolerance, so that a higher proportion of latewood and consequently a higher MOE$_{site}$ (due to the greater stiffness of latewood than of earlywood) would be obtained. The observed relationship between latewood width proportion and soil litter N/P ratio ($r = -0.6781$, $p < 0.0001$) supports this hypothesis. In a study with young *Pinus radiata* stands, Watt *et al.* (2006) also observed significant correlations between organic phosphorus and MOE, although

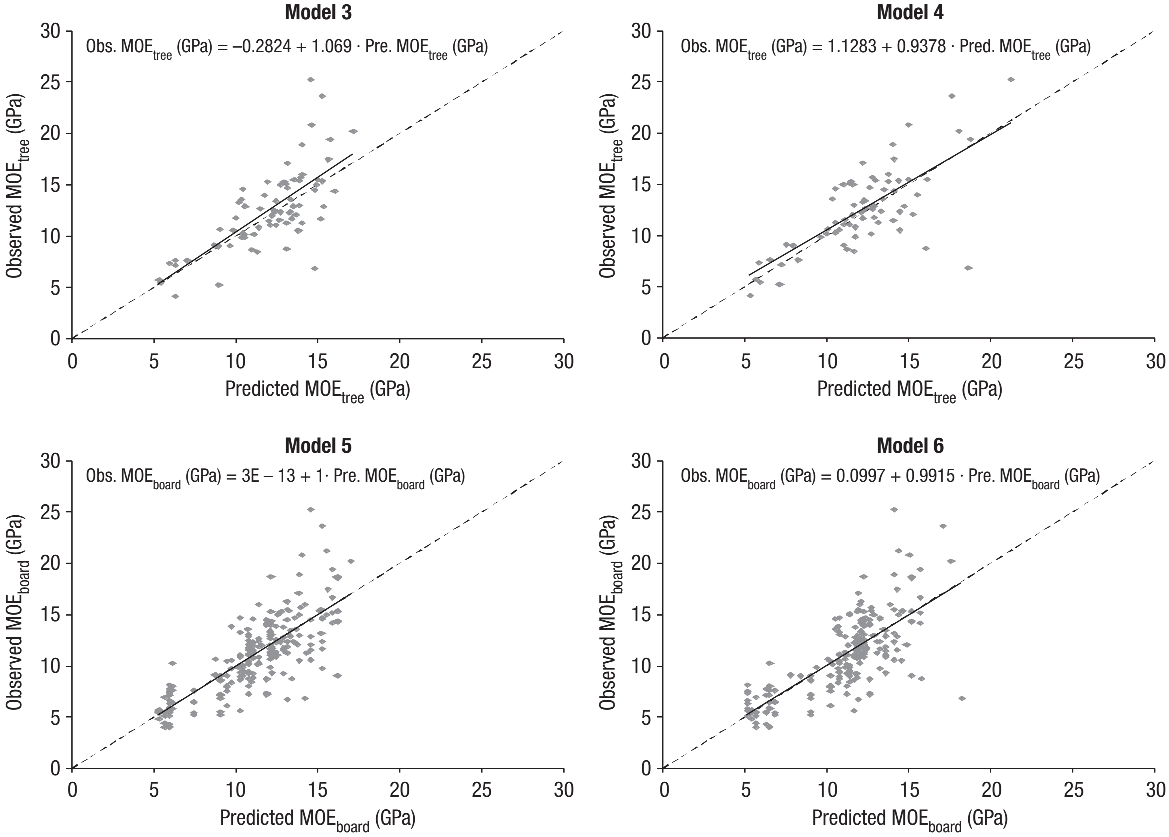

Figure 1. Plots of observed versus predicted values of MOE at tree (upper row) and board (lower row) level obtained from the models including wood density and site variables as independent variables (left) and from the models that do not include these variables (right). The solid line represents the linear model fitted to the scatter plot of data, and the dashed line is the 1:1 line.

the results indicated that MOE was relatively insensitive to P fertilization (with considerable increments, in the order of two- to three-fold).

The significant and positive linear relationship between MOE_{site} and mean annual temperature and mean minimum annual temperature may be due to the effect

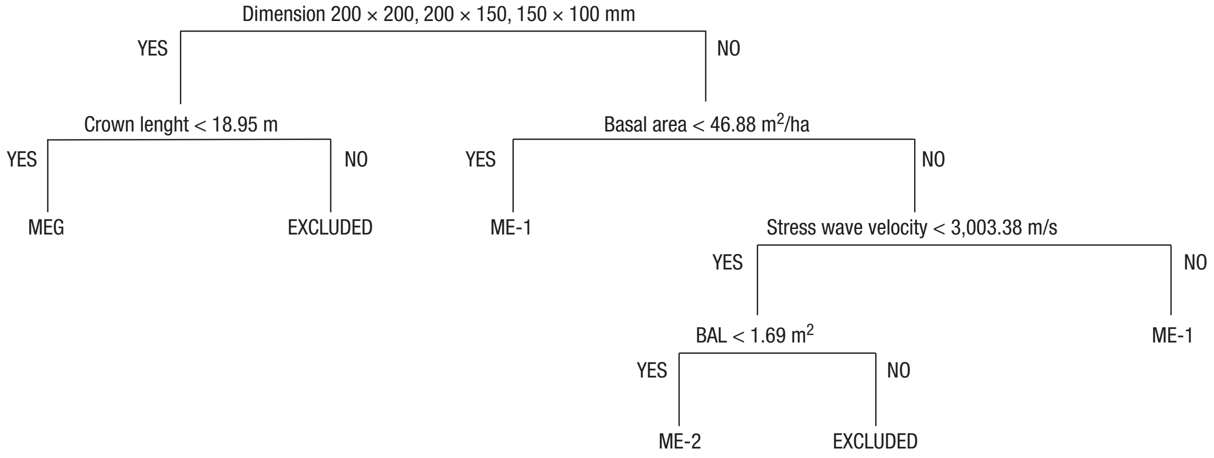

Figure 2. Classification tree for estimating the visual grade according to standard UNE 56544:2011 (AENOR, 2011) for *Pinus pinaster* timber in Galicia. The rpart package from R (R Development Core Team, 2011; Therneau and Atkinson, 2012) was used to obtain the classification tree.

of temperature on latewood development. As latewood fibres are stiffer than earlywood, higher temperatures (especially in autumn) could yield a higher percentage of latewood, and therefore a higher overall MOE of the timber. Similar results have been reported for young *Pinus radiata* stands (Watt *et al*., 2006; Watt *et al*., 2008).

The $\mathrm{MOE}_{\mathrm{site}}$was also strongly correlated with site index. Watt *et al*. (2006) reported that site had a significant effect on MOE in young *Pinus radiata* stands; however, Liu *et al*. (2007) did not observe a significant correlation between site index and MOE in *Picea mariana* stands, although these authors considered that this was due to the lack of variability in site quality. The significant negative correlation observed between basal area and $\mathrm{MOE}_{\mathrm{site}}$ is consistent with findings for other tree species, such as *Pseudotsuga menziesii* (Walford, 1985), *Picea abies* (Kliger *et al*., 1995), *Pinus resinosa* (Deresse *et al*., 2003), *Pinus radiata* (Lasserre *et al*., 2004) or *Picea sitchensis* (Moore *et al*., 2009).

Neither the number of stems per hectare nor stand age ($p = 0.5668$) were significantly correlated with $\mathrm{MOE}_{\mathrm{site}}$. Similar results were reported by Moore *et al.* (2009) for *Picea sitchensis* stands in the United Kingdom, where evidence of correlations between these variables and MOE was inconclusive, although stand age and number of stems per hectare were finally included as independent variables in a linear model proposed by these authors to estimate MOE. Gains in MOE attributable to increased number of stems have been found in different studies (*e.g.* Biblis *et al*., 1995; Wang and Ko, 1998; Chuang and Wang, 2001; Wang *et al*., 2001a; Zhang *et al*., 2002; Lasserre *et al*., 2004; 2008; Waghorn *et al*., 2007a, b). However, in the present study, this variable did not have a significant effect, probably because the range of stand densities (175-726 stems/ha) was not large enough. Nevertheless, the above mentioned correlations should be confirmed with further research including a database with a broader range of ages and number of stems per hectare to identify the key variables affecting the $\mathrm{MOE}_{\mathrm{site}}$.

Effect of site, tree and stand variables on mean tree $\mathrm{MOE}_{\mathrm{tree}}$ and $\mathrm{MOE}_{\mathrm{board}}$

The strong and positive correlation observed between MOE and stem slenderness has a sound theoretical basis. Based on Euler's buckling formula, the critical height ($h_{critical}$) that a tree stem can reach before it undergoes elastic buckling depends on MOE, green wood density (ρ_{green}) and stem diameter (DBH), as in the following expression (Greenhill, 1881):

$$h_{critical} = K\left(\frac{MOE}{\rho_{green}}\right)^{1/3} DBH^{2/3} \qquad [5]$$

where K is a constant. Under competition, light demanding species, such as maritime pine, give priority to height growth at the expense of diameter increment, which increases the stem slenderness. When tree heights are relatively close to the critical buckling height, alterations in wood properties may successfully prevent Euler buckling by increasing the density-specific stiffness ($\mathrm{MOE}/\rho_{\mathrm{green}}$); this is mainly accomplished through increments in MOE, as green density is relatively constant (Lasserre *et al*., 2005; Watt *et al*., 2006). Similar results were found for other coniferous species such as *Cupressus lusitanica* (Watt *et al*., 2008), *Picea mariana* (Lei *et al*., 2005; Liu *et al*., 2007) and *Pinus taeda* (Roth *et al*., 2007).

Previous studies have also reported a strong negative relationship between DBH and MOE, *e.g.* in *Picea abies* (Haartveit and Flate, 2002), four softwood species (Wang *et al*., 2002), *Picea mariana* (Liu *et al*., 2007) and *Picea sitchensis* (Moore *et al*., 2009). This can be explained by assuming that trees with higher DBH have wider rings and, consequently, lower percentage of latewood and, as latewood fibres are stiffer than earlywood, the lower percentage of latewood in larger trees could account for the low MOE observed in these trees. Such a negative linear correlation implies that selection of a tree by diameter alone could negatively affect the mechanical properties of wood. However, selection based on the slenderness ratio or a combination between diameter and acoustic velocity appears to be associated with better mechanical properties (Merlo *et al*., 2008).

The negative and significant correlation observed between crown ratio and MOE at tree and board level was also reported for other coniferous species such as *Picea mariana* (Liu *et al*., 2007) and *Picea sitchensis* (Moore *et al*., 2013).

As regards the observed effect of competition on MOE, our results are consistent with previous reports of a significant negative relationship between rate of diameter growth and stiffness (Walford, 1985; Kliger *et al*., 1995; Deresse *et al*., 2003, or Lasserre *et al*., 2004). In a study of the effect of silvicultural management on wood properties in *Pinus sylvestris* and *Picea abies*, Ikonen *et al*. (2008) observed a similar effect of competition on wood properties. These authors fitted ring-based models to estimate wood density along the stems for both species, and both models predicted slightly lower wood density for dominant trees in thinned and unthinned stands and, as a consequence, lower MOE.

The strong and positive relationship between MOE at tree and board level and latewood width proportion ($r = 0.6319$, $p < 0.0001$) was probably due to the importance of this proportion in wood density. Studies assessing genetic and phenotypic effects on wood characteristics in *Pinus pinaster* have indicated that earlywood characteristics are prone to genetic control, whereas latewood components are more strongly influenced by environmental factors (Gaspar *et al*., 2008a,b). These studies have also indicated the high heritability of wood density and the high genetic correlation between wood density and early wood density (Gaspar *et al*., 2008a), suggesting that breeding programmes to select this wood property by increasing either earlywood density, latewood percent, or both of these traits, would be profitable.

The observed positive correlations between the withinring density parameters, based on the earlywood-latewood boundary, and MOE have been also previously reported, *e.g.* for *Picea sitchensis* (Gentner, 1985), for *Larix kaempferi* (Takata and Hirakawa, 1996) and for *Pseudotsuga menziesii* (Rozenberg *et al*., 1999).

Visual grading

Crown length was the main predictor variable in the classification tree obtained. This parameter classified the pieces in MEG or "excluded" categories for materials thicker than 70 mm. Values of crown length higher than 18.95 m led to the pieces being categorized as "excluded", independently of other tree or stand variables. Basal area was the main predictor variable for materials thinner than 70 mm. Tree materials from stands with a basal area smaller than 46.88 m^2/ha were categorized as ME-1 pieces. Stress wave velocity and basal area of larger trees were also significant predictors for classifying the sample pieces for materials thinner than 70 mm. Considering all sample pieces, 70.09% of the pieces were correctly classified, with 95.05, 76.94 and 25.00% of correct classifications for "MEG", "ME1" and "ME2" categories, respectively. The percentage of "ME-2" category correctly classified was very low, although 64% of these pieces were classified as "excluded". The most critical error of the proposed tree would be classification of excluded material in some of the structurally-apt material categories ("MEG", "ME1" and "ME2"); only 4.46% of the pieces were wrongly classified in this way. This type of wrong classification constitutes a loss in safety in the structural use of the products obtained from the graded stems. Therefore, from a conservative point of view, high safety factors should be applied in further calculations. On the other hand, the probability of excluding a structurally-apt piece (14.29%) should be minimized as it represents an underestimation of the quality of the material and a wrong reduction in the timber valuation.

Since the classification obtained in this study is based on a limited number of sample plots, the approach should be considered preliminary. Nonetheless, the method appears to be suitable as a first step in forest management decision-making regarding the most appropriate silvicultural schedule for obtaining structural timber in *Pinus pinaster* stands.

Conclusions

Structural static bending modulus of elasticity (MOE) is an important indicator of timber quality. In this study, the influence on MOE of site characteristics, competition and tree and stand variables was analyzed, and a stepwise regression method was used to identify the best variables, including acoustic velocity and wood characteristics, for estimating MOE at three different levels: site, tree and board. The results indicate that acoustic technology is effective for evaluating the structural quality of standing trees. The inclusion of acoustic velocity in this type of models would improve quantification of the effects of forest management and silvicultural treatments on wood quality and selection of the best material for tree breeding programmes. Prior classification of industrial supplies, based on the acoustic velocity of standing trees, would improve utilization of the timber and thus provide significant financial advantages to the industry.

More than 52% of the total variation in modulus of elasticity was attributed to between-stand differences and the mean annual temperature and the soil litter N/P ratio were the site variables more directly related to MOE. The influence of environmental factors was also pointed by the inclusion of site index in the models being excluded the edaphic and climatic variables. However, as the results are based on data from 10 pure and even-aged stands, further studies on the influence of this kind of variables on the wood properties should be carried out by analysing additional samples.

Nevertheless, the above-mentioned restriction does not reduce the value and applicability of the models developed for predicting MOE. In addition, the simple classification system presented enables preliminary assessment of the visual grade for structural timber of any *Pinus pinaster* standing tree by using common tree and stand variables and acoustic velocity, while minimizing overestimation of quality in the structural grade assignation process.

Acknowledgements

This work was mainly carried out within the Galician regional project PIDGT (07MRU004CT) and the national project MICINN PSE.310000-2008 co-financed with FEDER funds from the European Union. The financial support is gratefully acknowledged. We also thank Miguel Romero and Fernando Gómez who collaborated in field and laboratory work, as well as all staff at the Exfopino sawmill who helped in the sawing process.

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