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RESEARCH PAPER

Use of non-destructive test methods on Irish hardwood standing trees and small-diameter round timber for prediction of mechanical properties

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Abstract

• ***Key message*** **Mechanical properties of small-diameter round timber from hardwood thinnings of common alder (*Alnus glutinosa* (L.) Gaertn.), European ash (*Fraxinus excelsior* L.), European birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.), and sycamore (*Acer pseudoplatanus* L.) can be evaluated by non-destructive testing on either standing trees or green logs without wood density determination. Velocity differences between acoustic and resonance methods are influenced by tree species and age. Tree diameter improves the estimation of bending strength but not of stiffness.**

• ***Context*** There is a need for a reliable, fast, and inexpensive evaluation method to better sort hardwood thinnings according to mechanical properties for use in potential added-value applications.

• ***Aims*** The estimation by non-destructive testing of mechanical properties of round small-diameter timber of four hardwood species (common alder, European ash, European birch, and sycamore).

• ***Methods*** Acoustic velocity was measured in 38 standing trees and resonance velocity was recorded in green logs from these trees. The logs were then dried and tested in bending. Estimation models to predict mechanical properties from non-destructive testing measurements were developed.

• ***Results*** Large differences between velocities from acoustic and resonance techniques were found. Models based on both non-destructive testing velocities together with a species factor are well correlated with bending modulus of elasticity while models including tree diameter are moderately well correlated with bending strength. Inclusion of density in the models does not improve the estimation.

• ***Conclusion*** Models based on acoustic measurements on standing trees or resonance on green logs together with tree species and diameter provide reliable estimates of mechanical properties of round timber from hardwood thinnings. This methodology can be easily used for pre-sorting material in the forest.

Keywords Bending strength · Broadleaf thinning · Longitudinal frequency · Modulus of elasticity · Stress waves · Wind effect

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1 Introduction

Guidelines for initial thinning of Irish hardwoods (Short and Radford 2008) recommend the removal of diseased trees, competitors of selected high-quality trees, and trees removed for extraction racks, to favor the growth of selected potential crop trees, maintain stand health and vigor, and provide access for future management. Hawe and Short (2016) have presented a review of best hardwood thinning practices. Although it is still not clear if thinning increases or reduces softwood timber quality (Krajnc et al. 2019a), thinning is always recommended in the case of hardwoods. Trees felled (thinnings) during this initial thinning have small diameters and are considered low quality. In Ireland, hardwood thinnings are mainly used for energy production (Doran 2012; Mockler 2013) and are also used in chipped form in the manufacture of wood-based panels or in the pulp/paper industry (Campion and Short 2016). There is commercial value in seeking to use hardwood thinnings in higher value-added end uses as structural components within the construction industry and to develop its volume use in local rural industry (Wolfe and Moseley 2000; Cumbo et al. 2004; Gorman et al. 2016).

The development of new products utilizing hardwood thinnings requires knowledge of the physical and mechanical properties of the materials. Non-destructive testing techniques are commonly used for estimation of wood properties in forest, sawmill, and existing structures (Ross 2015). Non-destructive testing can be divided in global techniques (ultrasound waves, stress waves, and resonance) and local techniques (probing, coring, and drilling). The former techniques are mainly focused on estimation of static modulus of elasticity (MOE) and bending strength (f_m, formerly referred to as MOR) (Jayne 1959; Auty and Achim 2008; Íñiguez-González et al. 2019), and the latter on estimation of density (Llana et al. 2018; Fundova et al. 2019; Martínez et al. 2020). It is also common to combine different non-destructive techniques for better estimation results (Divós and Tanaka 1997; Vössing and Niederleithinger 2018). Non-destructive testing has the potential to provide low-cost timber quality assessment, which could be used in the forest to segregate logs into different end use categories. The estimation of mechanical properties of timber from standing trees or green logs has many benefits for growers and processors, as decisions taken at an early stage can result in cost savings.

Much research has been carried out to establish relationships between non-destructive testing measurements and the mechanical properties of wood. Most of this work has focused on softwoods with a relatively small number of studies on hardwoods. Non-destructive testing studies have been carried out at different stages in the wood processing chain including on standing trees, harvested logs, round timber, and sawn timber boards. In the case of hardwood thinnings, the small-diameter logs are not suitable for sawing because of the low yield and high processing cost. Therefore, the potential end uses of this material are likely to utilize the material in the round. The use of round timber instead of sawn timber presents several advantages. According to Wolfe (2000), round timber represents a more efficient use of material than sawn timber with higher load capacity (up to 5 times more) than timber sawn from it. When round timber is sawn, wood fibers are cut around knots leading to stress concentrations.

The most common non-destructive testing technique used on standing trees for mechanical properties' estimation is based on measurement of stress wave velocity (Wessels et al. 2011). On green logs, longitudinal vibration techniques are more commonly used (Lindström et al. 2002). Several methods for density estimation on standing trees are available including increment boring, penetration resistance, nail withdrawal, and resistance drilling, and these have been evaluated by Gao et al. (2017), who concluded that the drilling resistance method is the fastest and most accurate. On the other hand, it is also the most expensive approach. Furthermore, some authors have estimated MOE using non-destructive testing devices on cores extracted from standing trees (Yang and Fortin 2001; Chen et al. 2015; Desponts et al. 2017).

Most previous research studies have focused on estimation of mechanical properties of sawn timber from measurements on standing trees or logs. Several such studies have focused on softwoods (Ross et al. 1997; Tsehaye et al. 2000; Santaclara and Merlo 2011; Moore et al. 2013; Bertoldo 2014; Gil-Moreno and Ridley-Ellis 2015; Butler et al. 2017; Krajnc et al. 2019b; Simic et al. 2019). Significantly fewer authors have carried out studies on hardwoods (Casado et al. 2013; Bertoldo 2014). Some authors have tested round timber in bending correlating the results with non-destructive testing measurements. Most of these studies tested small-diameter round timber from thinnings, which according to Wolfe (2000) had a diameter smaller than 230 mm. On small-diameter timber, determination coefficients (R^2) ranging from 0.60 to 0.75 between global MOE in bending (MOE_m) and longitudinal dynamic modulus of elasticity ($Edyn_0$) were reported by Vries and Gard (1998), Wang et al. (2002), and Hermoso et al. (2007), while between local MOE and $Edyn_0$, they ranged from 0.49 to 0.67 (Aira et al. 2019; Vega et al. 2019). According to Krajnc et al. (2019c), who tested three softwood species with diameters from 250 to 410 mm, the estimation of mechanical properties of sawn timber from acoustic velocities on standing trees is better in small-diameter trees, as no correlation was found in the larger-diameter trees. In addition to longitudinal measurements on small-diameter logs, Wang et al. (2002) measured transversal vibration and found higher estimation R^2 values using transversal vibration (from 0.85 to 0.95).

Pelizan (2004) tested twenty-five 6-m-long roundwood logs of dry lemon-scented gum (*Eucalyptus citriodora* Hook.) using an ultrasound wave device and three-point bending tests. MOE_m and bending strength for lemon-scented gum could be estimated from the $Edyn_0$ with R^2 ranging from 0.48 to 0.83 and from 0.49 to 0.74, respectively. The R^2 values were dependent of the relative proportion of sapwood and heartwood, increasing with decreasing proportions of heartwood. Vega et al. (2019) tested 216 small-diameter (60, 80, and 100 mm) cylindrical timber specimens of dry sweet chestnut (*Castanea sativa* Mill.) using a stress wave device and four-point bending tests. Local MOE_m from the velocity and $Edyn_0$ was estimated with R^2 of 0.64 and 0.67, respectively. The estimates of bending strength were poor.

The main goal of the current research work is to estimate the mechanical properties of round timber from Irish hardwood thinnings using non-destructive testing on standing trees and on green logs, and to determine the best approach to apply in the forest taking into account factors such as stem diameter and species. Three objectives were defined for investigation: first, the influence of measurement position around the tree on non-destructive testing results; second, the differences between stress wave on standing trees and vibration results on green logs; and third, the estimation of mechanical properties from non-destructive testing results..

2 Materials and methods

2.1 Materials

A total of 38 logs with mid-diameters between 80 and 180 mm and lengths 25 times the diameter were selected for testing from first and second thinnings of four Irish-grown hardwood species: common alder (*Alnus glutinosa* (L.) Gaertn.), European ash (*Fraxinus excelsior* L.), European birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.), and sycamore (*Acer pseudoplatanus* L.). The trees were chosen from seven stands located in the Republic of Ireland (Table 1). Stand No. 5 had special characteristics because the birch was mixed with other species (European beech (*Fagus sylvatica* L.) and European oak (*Quercus robur* L.)). Furthermore, the 1st thinning material was extracted from a flat area on the top of a hill while the 2nd thinning was midway down the slope of the hillside. Only one log from the bottom part of each tree (butt log) with an overall length of 25 times its mid-diameter was selected, because of the lack of straightness in the top part and the reduced stem diameter. Furthermore, non-destructive testing measurements on butt logs have been found to provide better estimates of MOE than those on upper logs (Tsehaye et al. 2000; Rais et al. 2014).

2.2 Non-destructive testing experiments

Two different non-destructive testing approaches were used. The time-of-flight (TOF) of acoustic stress waves over a 1-m length was measured on standing trees at the eight different cardinal and intercardinal points using a TreeSonic (Fakopp, Sopron, Hungary) device and the acoustic velocity was determined. A Mechanical Timber Grader MTG (Brookhuis, Enschede, Netherlands) was then used to determine the fundamental frequency (f) in the longitudinal direction on green logs just after harvesting (Fig. 1). The resonance longitudinal velocity for the logs was calculated using Eq. 1:

$$Vel_0 = 2 \cdot f \cdot L \tag{1}$$

where Vel_0 is the acoustic velocity in longitudinal direction (m s^{-1}), f is the fundamental frequency (Hz), and L is the log length (m).

Velocities obtained from these measurements were adjusted to a reference moisture content (MC) of 12% based on the works of Sandoz (1989, 1993). The adjustment factor applied was 0.8% per 1% MC below fiber saturation point (FSP). It is well known that the influence of MC on non-destructive testing results is much stronger below than above FSP. According to Sandoz (1993), the influence is at least eight times more on ultrasound velocity. A similar effect was reported by Unterwieser and Schickhofer (2007) and Rais et al. (2020) on longitudinal vibration. For that reason, since green logs had an average MC of 88%, the correction was applied for a reduction in MC from 30 to 12%. $Edyn_0$ was then calculated from density and velocity previously adjusted to 12% according to Eq. 2:

$$Edyn_0 = \rho \cdot {Vel_0}^2 \tag{2}$$

where $Edyn_0$ is the dynamic MOE in longitudinal direction (N m^{-2}) and ρ is the log density (kg m^{-3}).

The importance of determining Poisson ratios, for inclusion in the Edyn calculation to accurately determine the MOE, was reported by several authors, who used high-frequency ultrasound devices and small clear specimens (Ozyhar 2013; Niemz and Bachtiar 2017; Suryoatmono 2017; Gonçalves et al. 2019). However, in the present study, Poisson ratios were not taken into account in the Edyn calculation due to high slenderness of the test specimens.

2.3 Mechanical testing

After drying the roundwood to a MC below 20%, four-point bending tests were conducted over a span of 18 times the mid-diameter to obtain the global MOE_m and f_m. Although there is a specific standard for testing structural round timber (EN14251 2003a), this standard is only designed for local MOE in bending. Therefore, EN408 (2012), which is suitable for rectangular and circular solid timber sections, was followed to determine the MOE_m (Fig. 1).

Table 1 Forest stand information and felled tree mean characteristics

Stand							Felled trees		
Stand No.	Species	Thinning	Latitude (º)	Longitude (º)	Age (year)	Trees per ha	No.	DBH (mm)	Height (m)
1	Ash	1st	54.05133	− 7.30363	15	2500	5	127	13.6
2	Sycamore	2nd	54.05458	− 7.32214	23	1650	3	151	18.6
3	Ash	2nd	53.25189	− 7.15134	21	1075	5	133	13.8
4	Alder	2nd	53.24934	− 7.15756	21	2650	5	132	12.6
5	Birch	1st and 2nd	51.91972	− 8.03055	21	Mix	5	123	11.3
6	Sycamore	1st	53.47110	− 8.40793	15	3325	5	118	9.0
7	Alder	1st	53.74570	− 8.64617	13	3475	5	92	8.9

DBH, diameter at breast height

2.4 MC and density determination

The ovendry method, according to standard EN 13183-1 (2002), was applied to determine the MC in green and dry conditions using disk specimens free of knots and resin pockets according to EN 408 (2012). Furthermore, the mass and dimensions of the disk specimens were recorded to determine the green density.

3 Results

3.1 Influence of measurement position

Table 2 summarizes mean values of the eight TreeSonic velocity measurements taken at eight cardinal and intercardinal points around the trees, together with coefficients of variation (COV) and *P* values from analysis of variance (ANOVA).

ANOVA was carried out in order to determine if there are significant differences in TreeSonic velocity around the tree. As all *P* values in Table 2 are higher than 0.05, no significant differences were found for the 95% confident level. However, in the stands No. 3 and 5.1, higher velocities were found in the 225° measurements (SW) with the values decreasing with position to a minimum in the 45° (NE) direction (Fig. 2). The differences between highest and lowest velocities are 6.2% in the case of stand 3 and 4.0% in the case of 5.1 that is not explained by the variability (Table 2). The main reason could be the typical Irish strong wind, which is predominantly from the SW direction. The windward face of the tree is under tension and this is where hardwoods produce reaction wood. These two stands were especially vulnerable to wind action due to their orientation.

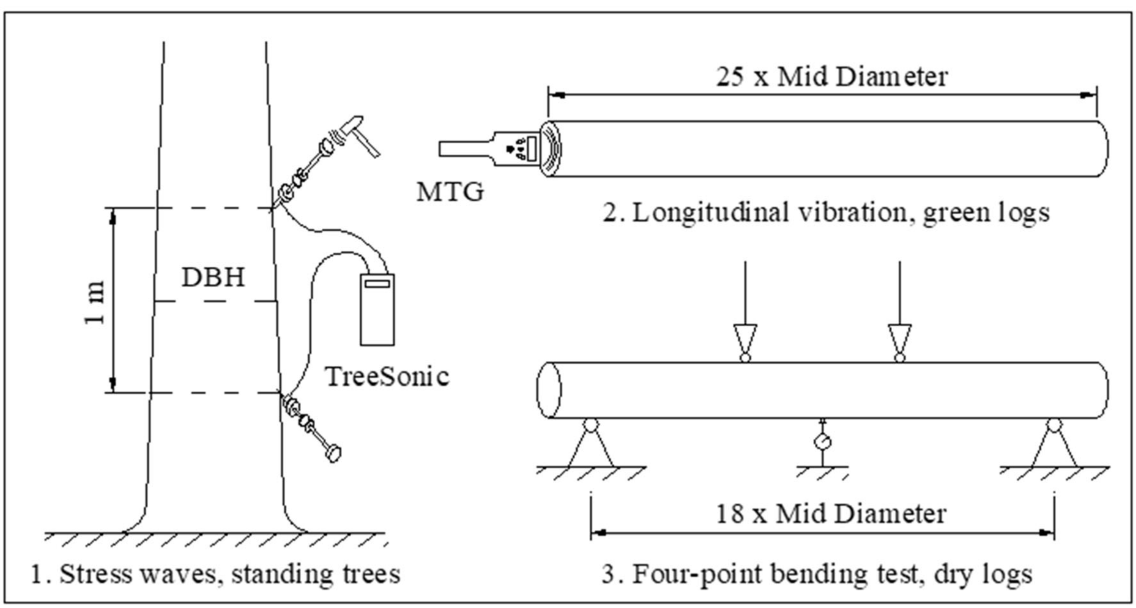

Fig. 1 Measurement set up. (1) On standing trees. (2) On green logs. (3) On dry logs

Table 2 Mean TreeSonic velocities recorded in eight different positions (cardinal and intercardinal points) around the tree

Stand	Velocity TreeSonic m s^{-1}									
	N 0°	NE 45°	E 90°	SE 135°	S 180°	SW 225°	W 270°	NW 315°	COV (%)	*P* value
1	4116	4112	4161	4135	4208	4214	4142	4142	0.9	0.995
2	4074	4106	4056	4028	3966	3975	4031	4075	1.1	0.949
3	4189	4147	4142	4195	4289	4398	4258	4308	2.0	0.473
4	3675	3716	3690	3757	3715	3702	3795	3718	1.0	0.989
5.1	4085	4074	4110	4163	4180	4236	4215	4138	1.3	0.539
5.2	4013	3979	3916	3911	3952	3955	4025	4051	1.2	0.969
6	3125	3119	3104	3105	3092	3122	3097	3092	0.4	1.000
7	3209	3162	3188	3181	3197	3224	3225	3155	0.8	0.968

3.2 Differences between results from different non-destructive testing devices

Table 3 summarizes and compares the mean velocities obtained using the TreeSonic and the MTG devices.

As expected, stress wave velocities (TreeSonic) are higher than those determined using longitudinal vibration (MTG) and on average are 18.6% higher (Table 3). Furthermore, these differences are expected to be even greater if the stress waves are measured from end-to-end as the longitudinal vibration was measured, because end-to-end velocities are always higher than surface velocities. Arriaga et al. (2017, 2019) reported velocities up to 4.4% higher in sawn timber. Table 3 also shows differences between velocity values from 1st and 2nd thinnings for both devices. Performing a *t* test, significant differences between 1st and 2nd thinning velocities were found in the case

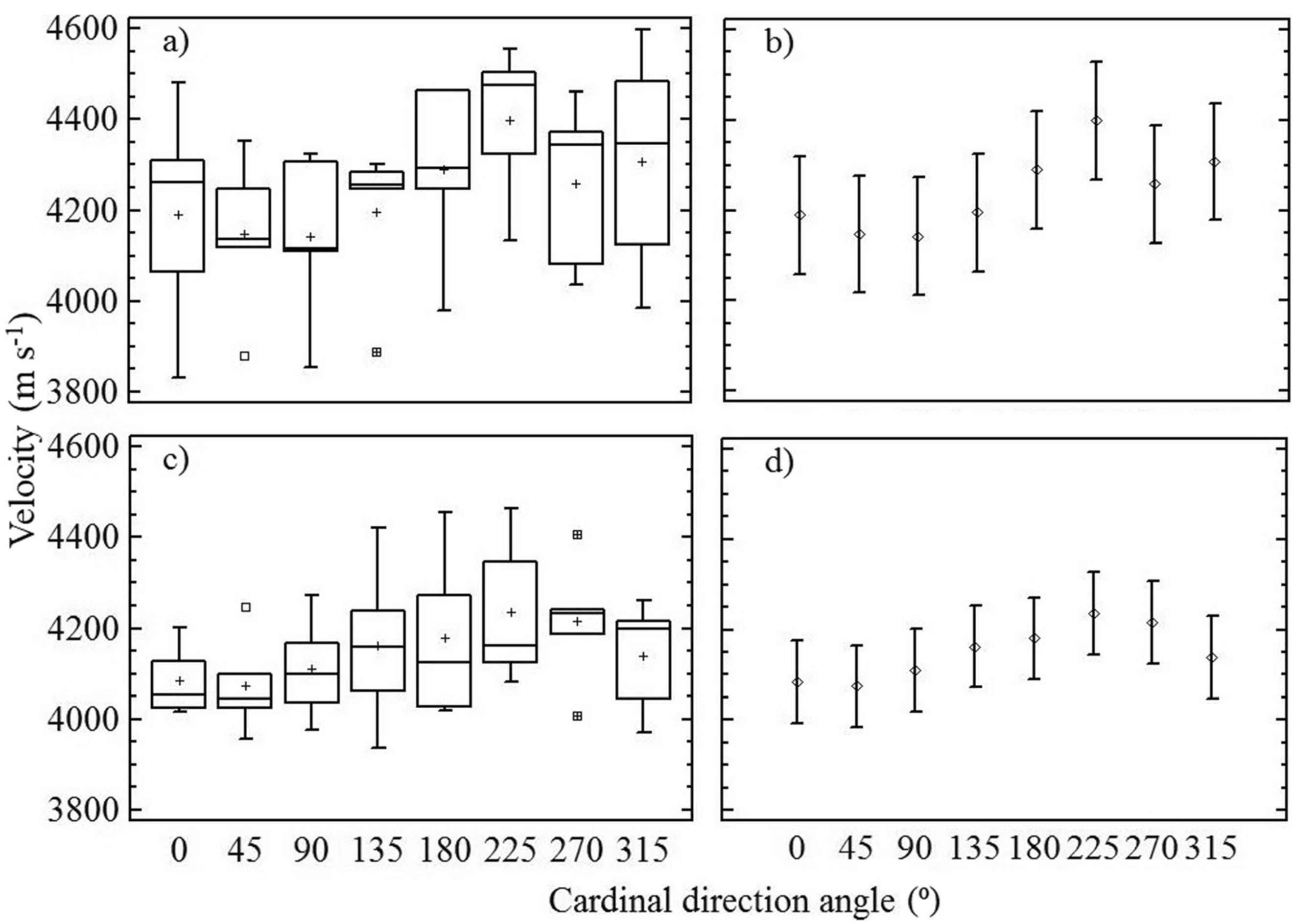

Fig. 2 ANOVA box and whisker plot and mean test for TreeSonic velocity around trees: (a) and (b) stand 3 ash; (c) and (d) stand 5.1 birch

of alder and sycamore, but not in the case of ash and birch (Fig. 3). Non-destructive testing velocities are higher in the 2nd thinning (except in birch) as was expected because 1st thinning trees have a larger proportion of juvenile wood compared with those from 2nd thinnings. However, densities are lower in the second thinning (except in birch). As was explained earlier, the birch stand was the same for 1st and 2nd thinnings and was mixed with two other species. Furthermore, 1st and 2nd thinnings in all species (except in birch) are from different stands so that other factors such as soil type and wind exposure may have an influence on the properties.

3.3 Mechanical properties' estimation

Table 4 shows mechanical properties obtained from four-point bending tests performed in the laboratory on dry logs and density obtained from disks. MOE_m and density were adjusted to 12% MC according to EN384 (2018).

In order to estimate the mechanical properties from non-destructive testing measurements, regression models were developed to estimate static MOE_m from velocity and $Edyn_0$ obtained from TreeSonic measurements on standing trees and from MTG velocity and $Edyn_0$ on green logs (Fig. 4).

Several other variables, such as species factor, density, DBH, number of annual rings, and thinning parameters, were included in the estimation models in order to improve the prediction of MOE_m. Only the species factor resulted in higher coefficients of determination. The final model is given in Eq. 3 and the model coefficients are presented in Table 5.

$$MOE_m = a \cdot (Vel_0 \text{ or } Edyn_0) + b \cdot Zald + c \cdot Zash + d \cdot Zbir + 0 \cdot Zsyc + e \quad (3)$$

where MOE_m is the static global modulus of elasticity in bending (N mm^{-2}), Vel_0 is the velocity obtained from TOF or longitudinal frequency (m s^{-1}), $Edyn_0$ is the dynamic modulus of elasticity determined from Eq. 2, and *Zald*, *Zash*, *Zbir*, and *Zsyc* are constants for alder, ash, birch, and sycamore, respectively, which have a value of 1 for the tree in question and 0 otherwise.

Since the *P* values in the ANOVA table are less than 0.05, there is a statistically significant relationship between the MOE_m and the explanatory variables at the 95% confidence level. All the models presented similar R^2 being slightly higher using velocity. Therefore, MOE_m can be estimated on standing trees using TreeSonic velocity without the necessity to estimate the wood density in the forest. This is especially important in thinnings in order to minimize the timber quality evaluation costs.

Using the same approach used for developing MOE_m models, estimation models were also developed for f_m. In this case, the predictive power of the model was improved when species factor and log mid-diameter were included. The f_m model is given in Eq. 4 with the model coefficients given in Table 6.

$$f_m = a \cdot (Vel_0 \text{ or } Edyn_0) + b \cdot Zald + c \cdot Zash + d \cdot Zbir + 0 \cdot Zsyc + e \cdot \varnothing_{mid} + f \quad (4)$$

where f_m is the bending strength (N mm^{-2}) and $\varnothing_{mid}$ is the log mid-diameter (mm).

4 Discussion

4.1 Influence of measurement position

In the present work, no significant differences were found between the eight TreeSonic velocities around the trees.

Table 3 Non-destructive testing acoustic velocity on standing trees (TreeSonic) and green logs (MTG)

Species	Thinning	Velocity TreeSonic		Velocity MTG		Velocity difference (%)
		Mean (m s^{-1})	COV (%)	Mean (m s^{-1})	COV (%)	
Alder	1st	3609	4.6	3053	7.1	18.2
	2nd	4254	5.3	3419	3.1	24.4
	Both	3931	9.6	3257	7.5	20.7
Ash	1st	4738	4.5	4088	5.5	15.9
	2nd	4928	5.2	4185	2.7	17.8
	Both	4833	5.3	4136	4.5	16.9
Birch	1st	4734	2.7	3877	5.8	22.1
	2nd	4635	4.9	3704	8.4	25.1
	Both	4684	4.1	3791	7.5	23.6
Sycamore	1st	3537	9.4	3139	5.0	12.7
	2nd	4661	7.3	4034	5.5	15.5
	Both	3959	16.1	3475	13.5	13.9
All together		4372	12.9	3686	12.3	18.6

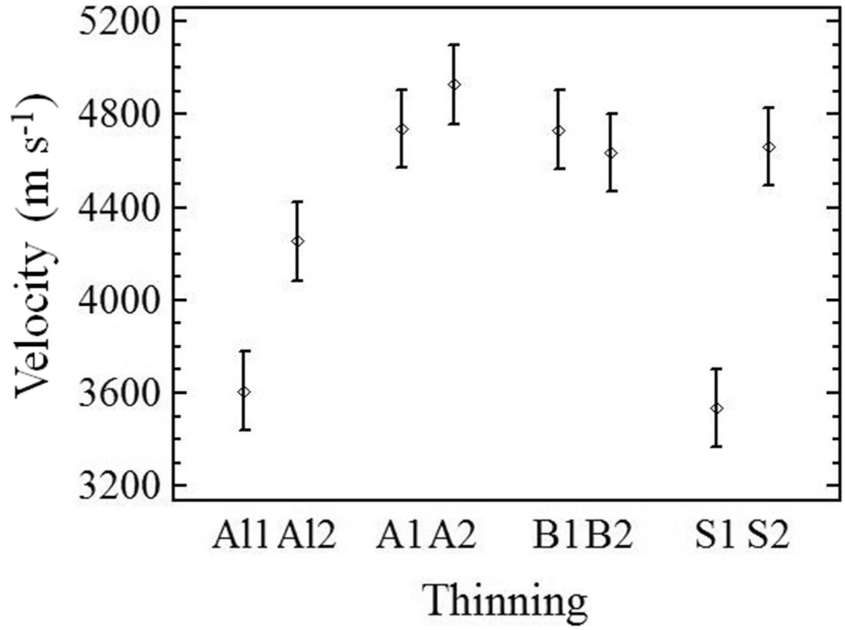

Fig. 3 ANOVA mean test for TreeSonic velocities of 1st and 2nd thinnings: Al, alder; A, ash; B, birch; S, sycamore

This is similar to the findings of Grabianowski et al. (2006), Lindström et al. (2009), Vihermaa (2010), and Gil-Moreno (2018) but contrary to those of Moore et al. (2009), Yin et al. (2010), and Díaz-Bravo et al. (2012). The results of the present work indicate that a single tree measurement is sufficient leading to significant time saving. However, as higher velocity values were found in the predominant wind direction than in the opposite direction for the most wind-exposed stands, the authors recommend that the mean of two diametrically opposite measurements be used, as was suggested by Toulmin and Raymond (2007), or a single measurement perpendicular to the predominant wind direction be used.

4.2 Comparison of non-destructive results on standing trees and green logs

Another important issue affecting non-destructive testing measurements is the higher velocities obtained from acoustic methods in comparison with resonance methods. This issue is well known in sawn timber (Haines et al. 1996; Íñiguez 2007; Llana et al. 2016) but has been less studied for stress waves devices on standing trees and resonance devices on green logs. In this study, velocity values ranging from 12.7 to 25.1% higher were found using stress waves compared with resonance methods. Several authors found a similar effect in softwoods with

Table 4 MC and mechanical properties obtained by four-point bending test on dry logs

Species	Thinning	MC		MOE_m		f_m		Density	
		Mean (%)	COV (%)	Mean (N mm^{-2})	COV (%)	Mean (N mm^{-2})	COV (%)	Mean (kg m^{-3})	COV (%)
Alder	1st	12.6	5.2	5735	10.5	61.83	16.8	498	7.1
	2nd	15.1	10.4	7740	11.9	51.79	24.4	481	4.6
	Both	13.8	12.5	6738	18.8	56.81	22.2	489	6.3
Ash	1st	18.2	8.1	10162	16.9	65.11	11.1	668	6.9
	2nd	18.4	9.4	9435	12.6	60.86	11.5	659	7.3
	Both	18.3	8.8	9799	15.5	62.99	11.8	664	7.2
Birch	1st	19.8	10.1	8076	13.8	47.33	18.9	592	3.9
	2nd	18.8	9.6	7519	13.2	49.75	14.3	606	2.1
	Both	19.3	10.2	7797	14.0	48.54	16.9	599	3.3
Sycamore	1st	10.3	8.0	6391	22.0	43.90	13.9	560	5.1
	2nd	14.4	9.9	8918	12.0	56.02	11.5	542	8.3
	Both	11.9	19.1	7339	24.2	48.45	17.7	553	6.6
All together		16.0	22.2	7949	23.1	54.50	20.7	578	12.8

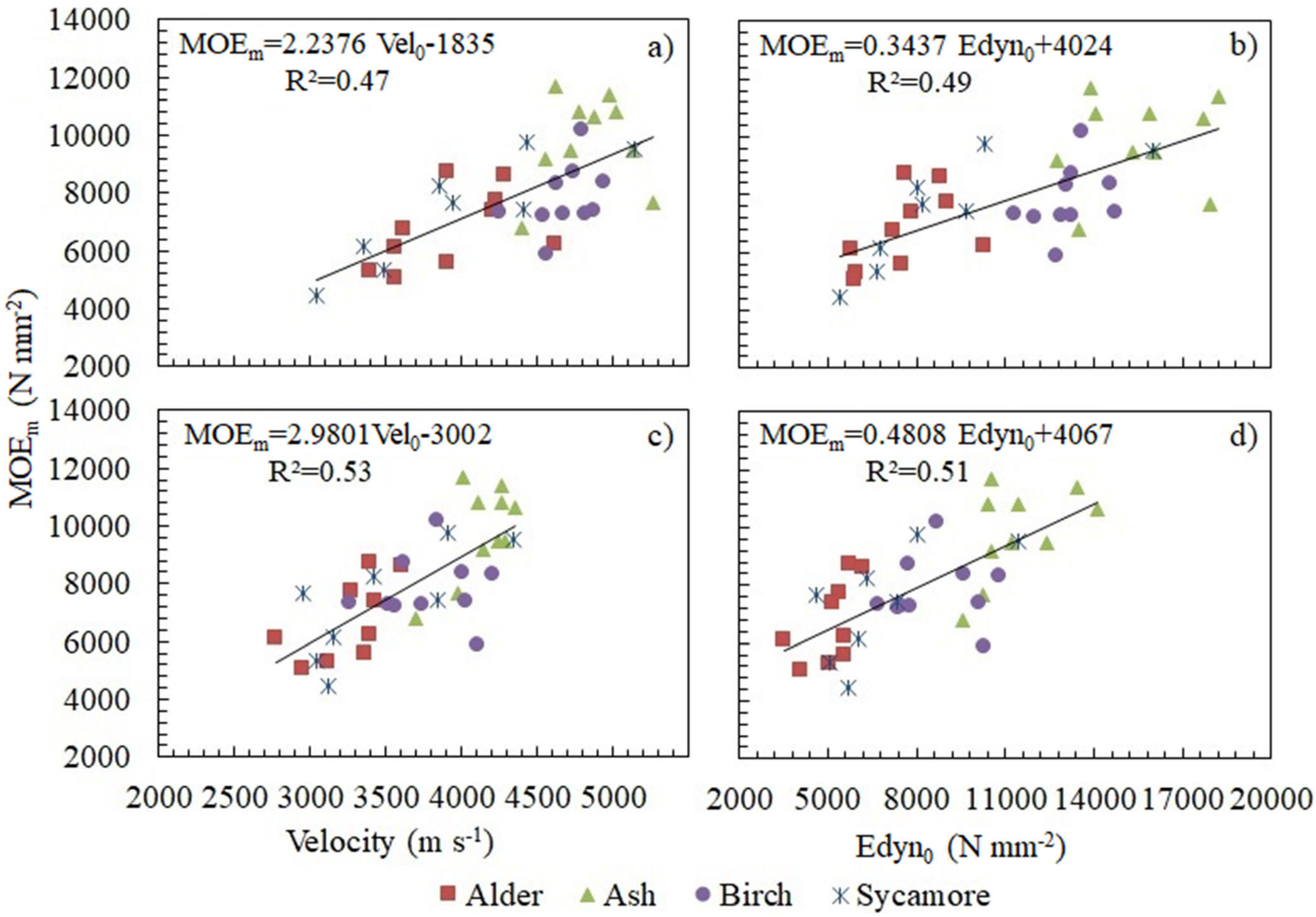

Fig. 4 Linear regressions between static MOE$_m$ and (a) TreeSonic velocity, (b) TreeSonic Edyn$_0$, (c) MTG velocity, and (d) MTG Edyn$_0$

variable differences. From the smallest to the highest, the differences were as follows: 9.5% Yin et al. (2010); 11.2% Simic et al. (2019); 12% Grabianowski et al. (2006); from 8.7 to 17.5% Chauhan and Walker (2006); from 16 to 31% Lasserre et al. (2007); 32% Mora et al. (2009); from 7 to 36% Wang et al. (2007). Furthermore, in hardwoods (*Eucalyptus* sp.), 20% was reported by Bertoldo (2014). Various theories have been used to explain these differences. Chauhan and Walker (2006) and Grabianowski et al. (2006) attributed the differences to the fact that stress wave devices measure outerwood containing more mature wood, while resonance devices assess the whole cross section. According to Bertoldo and Gonçalves (2015), acoustoelasticity could also explain these differences based on the variation in the velocity due to loading conditions: standing trees support their weight, while logs are free of loads. Wang et al. (2007) suggested that the differences are due to the type of wave propagation: dilatational waves in the case of TOF measurements on standing trees and one-dimensional longitudinal waves in the case of logs. Additionally, they found a smaller difference in small-diameter trees because stress waves would propagate in those cases more as one-dimensional longitudinal waves. Chauhan and Walker (2006) also found less difference in young trees. This is in agreement with the results of the present work, where lower velocity differences were found in the 1st than in 2nd thinning. Finally, according to Wang (2013), different TOF measurement devices used on standing trees may have different algorithms and trigger settings, making it

Table 5 Coefficients of the regression model for MOE$_m$ estimation (Eq. 3)

Variable	a	b	c	d	e	R2	P -value
Vel$_0$ TreeSonic	2.0500	− 544.94	667.72	− 1028.35	− 776.64	0.59	0.000
Edyn$_0$ TreeSonic	0.3735	− 126.02	− 23.09	− 1139.55	4022.53	0.56	0.000
Vel$_0$ MTG	2.5508	− 42.33	772.00	− 347.97	− 1524.13	0.58	0.000
Edyn$_0$ MTG	0.4702	181.80	309.48	− 414.97	4136.83	0.53	0.000

Table 6 Coefficients of the regression model for bending strength estimation (Eq. 4)

Variable	*a*	*b*	*c*	*d*	*e*	*f*	R^2	*P* value
Vel_0 TreeSonic	0.0049	4.60	10.18	− 5.04	− 0.21	56.11	0.44	0.002
$Edyn_0$ TreeSonic	0.0015	6.28	4.63	− 7.82	− 0.21	62.95	0.47	0.001
Vel_0 MTG	0.0091	5.46	8.46	− 4.28	0.20	42.90	0.46	0.001
$Edyn_0$ MTG	0.0021	7.26	5.02	− 5.09	− 0.18	57.65	0.48	0.001

difficult to compare results between authors using different devices.

4.3 Estimation of mechanical properties from non-destructive testing

Table 7 presents results from several authors, who used non-destructive testing devices on standing trees or logs. The bending tests were carried out either on the logs in roundwood form or on timber sawn from the logs.

In the present study, the MOE_m of round timber estimated from $Edyn_0$ and velocity had coefficients of determination R^2 of 0.56 and 0.59, respectively, in the case of the TreeSonic, and 0.53 and 0.58 in the case of the MTG. For bending strength estimation, R^2 varied from 0.44 to 0.48 for both devices. The R^2 values obtained are relatively low. The main reason could be the small number of data points for each species, as only five trees were tested on each kind, when it was possible. In any case, the R^2 values obtained are not too far away from those reported by other authors using larger samples (Table 7), e.g., Vega et al. (2019) obtained R^2 values from 0.64 to 0.67 when testing 216 small-diameter round sweet chestnut using a Microsecond Timer (equivalent to TreeSonic). Table 7 presents the results from other studies. It should be taken into account that it is difficult to compare results with other authors as there is a great disparity of methods used (different devices, different species, standing trees, green or dry logs, large or small diameter, testing round shape or sawn timber). Therefore, a great disparity of R^2 results was found (from 0.02 to 0.83 for MOE_m and from 0.03 to 0.81 for f_m). In agreement with other works, the MOE_m estimation models presented here have higher determination coefficients than those for f_m. Simic et al. (2019) found better mechanical properties' estimation from green logs' resonance than from standing trees' TOF velocities; in the present study, the R^2 values for the estimation models were similar between the two techniques as was reported by Moore et al. (2013). Simic et al. (2019) presented far higher R^2 values and Vega et al. (2019) slightly higher R^2 values when estimation was carried out from $Edyn_0$ than from velocity, while in the present work, slightly higher R^2 values were found using velocity than using $Edyn_0$. However, Simic et al. (2019) estimated mechanical properties of sawn timber while in Vega et al. (2019) and the present work, small-diameter roundwood mechanical properties were estimated. It appears that for small-diameter roundwood, estimation from velocity and $Edyn_0$ is similar. Furthermore, Table 7 does not show a difference in the coefficient of determination between softwoods and hardwoods.

Several studies have shown that estimation models and grading systems based on non-destructive testing measurements were improved by inclusion of the following parameters: diameter (Wang et al. 2004; Zhang et al. 2011; Ruy et al. 2018), ring width (Moore et al. 2013), height and basal area (Merlo et al. 2014). Diameter was found to increase the R^2 values from 0.30 to 0.44 in the f_m estimation models of the current study. However, the listed parameters had no significant influence in the MOE_m estimation models.

5 Conclusions

No significant differences were found in stress wave velocities from the eight measurements around the tree perimeter. However, higher velocities (from 4 to 6%) were found in some stands in the predominant wind direction associated with reaction wood.

Higher velocities were found using stress waves on standing trees than using resonance on green logs (from 12.7 to 25.1%). This difference depends on the species and is greater in the second than in first thinning. Nevertheless, the estimation of mechanical properties (MOE_m and f_m) of final dry roundwood is not affected as similar determination coefficients were found using stress waves or resonance. Prediction of mechanical properties was improved by including species as a factor, and in the case of f_m, also stem diameter (MOE_m R^2 0.59; f_m R^2 0.44). Estimation model results from acoustic velocity data (no requirement for wood density measurement) were not significantly different from those derived from $Edyn_0$ (that require wood density measurement) and, therefore, represent a consequent saving in time and cost.

Either stress waves on standing trees or resonance on green logs can be used to evaluate mechanical properties in the forest. Both are fast, reliable, and inexpensive methods of pre-sorting material based on quality. In the case of stress waves, it is recommended to use two diametrically opposite

Table 7 Determination coefficients of mechanical properties (MOE and bending strength) estimation models using non-destructive testing devices from several authors

Device	Variable	MOE_m R^2	f_m R^2	Species*	Bending test	Author
GrindoSonic MK5[(v)]	$Edyn_0$	0.72 0.76	0.58 -	Japanese larch Douglas fir	Roundwood	Vries and Gard 1998
Accelerometer[(v)]	$Edyn_0$	0.60 0.75	- -	Jack pine Red pine		Wang et al. 2002
Sylvatest Duo[(u)]	$Edyn_0$	0.48–0.83	0.49–0.74	Lemon-scented gum[(H)]		Pelizan 2004[(1)]
Sylvatest Duo[(u)]	$Edyn_0$	0.68	-	Salzmann pine		Hermoso et al. 2007
PLG[(v)]	Frequency	0.43	-	Spanish juniper		Villanueva 2009
Microsecond Timer[(s)]	$Edyn_0$	0.57[(L)] 0.49[(L)]	0.57 0.45	Salzmann pine Scots pine		Aira et al. 2019
Microsecond Timer[(s)]	Velocity $Edyn_0$	0.64[(L)] 0.67[(L)]	- -	Sweet chestnut[(H)]		Vega et al. 2019
Hitman ST300[(s)]	Velocity	0.53	0.59	Scots pine	Sawn timber	Auty and Achim 2008[(2)]
Hitman HM200[(v)]	Velocity	0.73	-	Maritime pine		Santaclara and Merlo 2011
Microsecond Timer[(s)]	Velocity	0.50	-	Black poplar[(H)]		Casado et al. 2013
IML Hammer[(s)] Hitman HM200[(v)]	$Edyn_0$ $Edyn_0$	0.49–0.83 0.45–0.80	0.81 0.68	Sitka spruce		Moore et al. 2013
USLab[(u)] Hitman ST300[(s)]	Velocity Velocity	0.64 0.78	0.67 0.38	Daintree stringybark[(H)] Lemon-scented gum[(H)] Saligna gum[(H)] Maritime pine		Bertoldo 2014[(1)]
TreeSonic[(s)] Hitman HM200[(v)]	$Edyn_0$ Velocity	0.27–0.57 0.63	- -	Noble fir Norway spruce Western hemlock Western red cedar		Gil-Moreno and Ridley-Ellis 2015
Hitman HM200[(v)]	Velocity	0.49–0.67	0.20	Loblolly pine		Butler et al. 2017
TreeSonic[(s)]	Velocity	0.43 0.05	0.29 0.03	Douglas fir Norway spruce		Krajnc et al. 2019c
		0.02	0.04	Sitka spruce		
Hitman ST300[(s)]	Velocity $Edyn_0$	0.41 0.55	0.27 0.47	Sitka spruce		Simic et al. 2019
MTG[(v)]	Frequency	0.47	0.28			
	$Edyn_0$	0.66	0.50			

Kind of device used: [(s)] stress waves, [(u)] ultrasound waves, [(v)] vibration

[(H)] Hardwood species

[(L)] Local MOE in bending

[(1)] Three-point bending test

[(2)] Small clear specimens

*Species' common names according to standard EN13556 (2003b) when possible, and when not according to Miller and Ilic (1992)

measurements or a single measurement perpendicular to the predominant wind direction.

The results, based on 38 logs from four hardwood species, require validation with a larger sample. An appropriate methodology for the evaluation of the mechanical properties of hardwood thinnings using non-destructive testing, including the identification of the relevant forestry parameters that should also be taken into account, has been developed and can be applied in future studies.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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