ISSN impresa 0717-3644
ISSN online 0718-221X
Maderas. Ciencia y tecnología 2025 (27): 40, 1-14
DOI: 10.22320/s0718221x/2025.40

NON-DESTRUCTIVE ESTIMATION OF WOOD DENSITY IN STANDING *Pinus brutia* TREES USING THE DRILLING RESISTANCE METHOD: RESULTS AND INSIGHTS

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ABSTRACT

In recent years, the use of drilling resistance method and devices which operate based on the method for non-destructive evaluation of wood has expanded, but research for density evaluation on standing trees remains limited. The study aimed to assess the effectiveness of the method through a device (IML RESI F500-S) in estimating wood density for standing Turkish red pine (*Pinus brutia*) trees. Increment core samples and measurement data were collected from stands of various ages and types in the Mediterranean region of Türkiye. Wood density data determined by x-ray densitometry were compared with estimates derived from charts of the device. The effect of drilling path direction was investigated on a group. Results showed that linear modelling by using the device data (obtained only by following the device manual) was moderately successful (r^2≈0,62) in estimating density for only a sampling group (S1: Consisting of trees at different age, on different diameter etc.; range of density: 0,270 g/cm^3; coefficient of variation:11 %). However, the other investigated group (S2), which had lower density variation due to less individual differentiation in terms of age, diameter etc., did not reveal a successful linear model. Solely the results for the subgroup 6th, showing lower density range than S1, demonstrated that even with lower density variation (cv≈7 %), standing tree wood density could be non-destructively estimated by a linear model (r^2=0,72) using the device data. However, the data of the group obtained by using increment cores to ensure proper alignment of the drilling. In this case accurate estimation required a drilling path perpendicular to annual rings and passing through the pith, but the current form of the device or such devices are unable to meet the requirement. The drilling resistance method has potential use in tree selection. To improve the device's accuracy, future research should focus on developing techniques or modifications of such device to ensure more consistent and reliable drilling paths for standing trees.

Keywords: Drilling resistance method, non-destructive testing of wood, *Pinus brutia,* wood density, standing tree assessment.

INTRODUCTION

Red pine (*Pinus brutia* Ten.) is naturally distributed mainly in the eastern Mediterranean region: Türkiye (Turkey), Greece, Cyprus, Syria, Palestine, Jordan, Iraq, and additionally some parts of northeastern neighbour countries of Türkiye; Crimea, Azerbaijan, Ukraine and Georgia. This species has a large ecological adaptability, growing performance and can be found in a variety of locations from sea level up to 1700 m. Planting this species is a top priority in various Mediterranean countries due to its relatively fast growth rate in favourable environment and to its wide ecological adaptability (Arbez 1974, Genç *et al.* 1997, Boydak 2004).

Wood density has long been considered an important wood quality attribute. Inexpensive, reliable, and rapid methods for assessing this trait are important in Forestry, especially in tree breeding programs. IML RESI F500-S is an instrument that measures and records penetration resistance (drilling resistance) of a fine drill needle. In recent years, the use of drilling resistance (known as drill resistance, micro-drill resistance) method for non-destructive evaluation of standing tree wood properties has been widening. In fact, the used device is quasi non-destructive, since the diameter of the needle is very small, and the weakening effect caused by the drilling hole is negligible. Because of this negligible destruction many researchers mentioned it as a non-de-

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Received: 04.10.2024 Accepted: 20.11.2025

structive instrument.

Drilling resistance measurements are mainly used by arborists or by construction engineers (Rinn *et al.* 1996, Costello and Quarles 1999, Eckstein and Sass 1994, Niemz *et al.* 2002) to detect defects either in living trees or in construction timbers. Earlier successful works on ring width and density characteristics investigating by the method through a device named as Resistograph was reported leading by Frank Rinn (Rinn *et al.* 1996), then the method and some other devices were also experimented for the evaluation of different wood properties in both standing trees and sawn timber (Chantre and Rozenberg 1997, Kappel and Mattheck 2003, Isik and Li 2003, Bouffier *et al.* 2008, Niemz and Mannes 2012, Icel and Guler 2016).

The used device creates and prints a graphic representation (charts) of the energy consumed by the electric motor as it penetrates the sample. Based on the wood's internal structure, a series of variables can be determined that explain its characteristics The total energy consumed in penetrating the sample is closely related to the material density. Due to the anatomical nature of pines, earlywood and latewood are separable depending on density. Denser wood (latewood) forms at the end of the growth ring. Thus, the charts appear as a succession of peaks and valleys, corresponding to the varying difficulty in penetrating the early- and latewood parts of annual rings (Figure 1a, and Figure 1b).

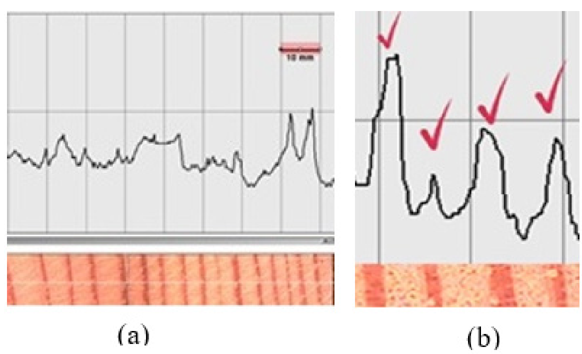

Figure 1: Matches between peaks - ring boundaries (a): General view; (b): In detail (Icel *et al.* 2015).

The relationship between amplitude and wood density values in loblolly pine (*Pinus taeda* L.) standing trees was investigated by Isik and Li (2003) who fitted a two-variable regression model for non-destructively determining wood density. Chantre and Rozenberg (1997) in douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Bouffier *et al.* (2008) in cluster pine (*Pinus pinaster* Aiton) and Johnstone *et al.* (2011) in victorian eurabbie (*Eucalyptus globulus subsp. Pseudoglobulus* (Naudin) J.B.Kirkp.) have obtained similar results with the same technique for the estimation of the mean wood density of populations in a tree breeding context. The linear relationship between wood density and drill resistance (amplitude data) was weak and positive at the individual-tree level (r^2 = 0,23), and stronger (r^2 = 0,47) at the family mean level for shortleaf pine (*Pinus echinata* Mill.) at the age of 25 (Gwaze and Stevenson 2008). The authors reported that genetic relationship between the two traits was moderately strong, and the method efficiency to select indirectly for wood density improvement was 86 % at the individual-tree level suggesting that it could reliably assess wood density in live shortleaf pine trees (Gwaze and Stevenson 2008).

This study aimed to point out some important details which possibly effect on the applicability of a device (IML RESI F500-S) works based on drilling resistance method as an efficient and a practical tool, for the determination of wood density of standing Turkish red pine (*Pinus brutia* Ten.). In addition to numerical results, we shared field experiences to contribute to future research.

MATERIALS AND METHODS

Plant material and experimental sites

Experimental site works were carried out at five experimental areas from Mediterranean regions of Türkiye (Table 1). Two types of data were collected for this research. Firstly, increment core samples and amplitude data were collected from five stands of different ages and types (planted and naturally regenerated) of red pine (*Pinus brutia* Ten.). On a first stage, 20 trees were sampled from each of the five experimental sites to evaluate the applicability of the method for density estimation of red pine (*Pinus brutia* Ten.) (Sampling Group 1).

Sampling technique

During this first field sampling, 100 increment cores and amplitude charts were collected from There was a typo here100 trees, but only 77 of them were useful for analysis (Table 1). Then 300 trees were sampled (Sampling group 2, one sample was unusable) from a genetic trial experimental site at younger age (AK) (Table 1). Wood density data determined by x-ray densitometry technique was compared with density data estimated from charts. AK experimental site is a young progeny (half-sibs) trial previously established on a flat terrain for genetic research.

The drilling direction should be perpendicular to the annual rings boundaries and should cross the pith (Rinn *et al.* 1996, Guller *et al*. 2012, Icel *et al.* 2015, Icel and Guler 2016, Gao *et al.* 2017) to have perfect match with ring boundaries. This is adjustable while working on cut samples, but nonadjustable on standing trees. Since there is not any positioning module to determine a perfect drilling direction, needle of the device can pass through pith or a different position (Figure 2a).

Depending on literature knowledge, increment cores can be used to determine the best drilling direction: Pirie *et al.* (2015), mention the geometric method (GM) and the Concentric Circles Method (CCM) as the two most accurate methods for estimating the pith offset for kauri trees.

The geometric method (GM) estimates the radius of the inner rings using their curvature (Figure 2a). This model requires that the inner rings form a complete arc and that this arc remains within the sample, making the height of the arc measurable (Duncan 1989, Pirie *et al.* 2015). The CCM (Figure 2b) uses a transparent overlay marked with patterns of concentric circles of annual rings located to match the curvature of the latewood arc of the innermost ring in the core with the curvature of the best-fitting circle. The centre of this best fitting circle was taken as the position of the pith. The CCM and GM applied for 50 of the 300 trees (at AK site where the other affecting factors variation such as age, diameter, genetic difference etc.is low) to establish the best possible drilling place of the device and to have the closest drilling direction to pith (Figure 2). For few trees, the increment cores did not include a complete arc; in these cases, the CCM method only applied. Forty-nine data for the sub-group of trees of which applied CCM and GM, were usable for statistical analysis. For the rest of the trees an increment core collected at breast height, and amplitude data were obtained from closest place to the coring hole (above/below, defect free place)

To have equal data for statistical analysis for revealing positioning effect of drilling, the other 250 data from AK site divided 5 equal sub-group, and in total 6 subgroups investigated.

Table 1: Information on experimental sites.

Region Name	Experimental site (abbreviation)	S1	N1	S2	N2	Tree age (average for **)	Altitude (m)	Coordinates
Antalya / Kepez	Kepez (AK)*	20	16	300	299	40	90	36° 55′ 18″ N 30° 37′ 00″ E
Burdur / Bucak	Melli (BM)**	20	15	-	-	100	350	37° 16′ 28″ N 30° 49′ 08″ E
Isparta / Sütçüler	Karadağ (SK)**	20	15	-	-	105	650	37° 30′ 49″ N 30° 51′ 56″ E
Burdur / Bucak	Pamucak (BP)**	20	15	-	-	112	800	37° 24′ 53″ N 30° 41′ 21″ E
Isparta / Gölhisar	Gölhisar (G)**	20	16	-	-	115	1100	37° 04′ 16″ N 29° 32′ 16″ E

*: Plantation; **: Natural stand; S: The number of trees sampled at field (S1: For Group1, S2: For Group 2); N: The number of samples used for statistical analysis (N1: For Group1, N2: For Group 2).

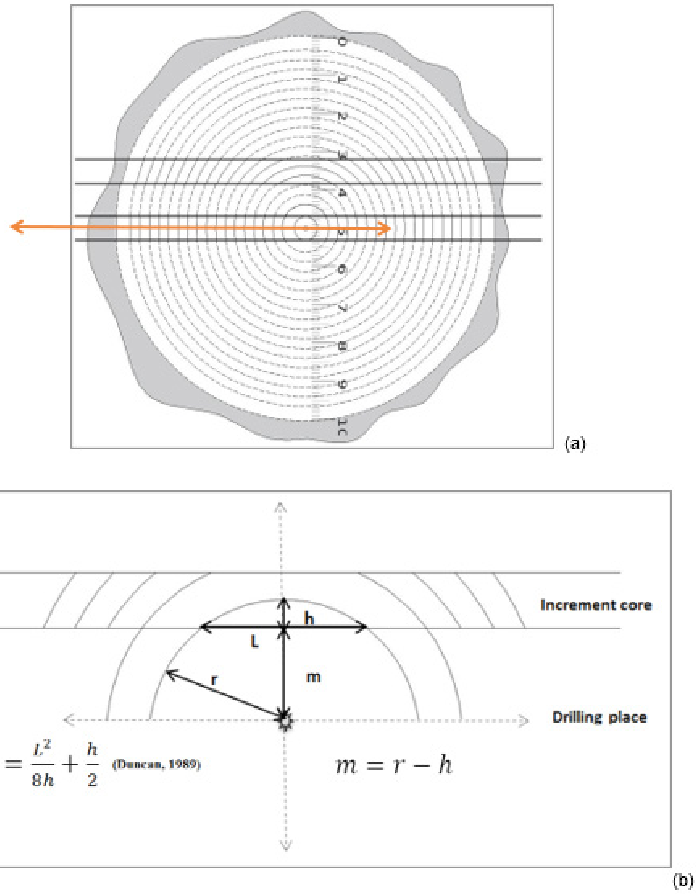

Figure 2: Estimation of drilling place by applying CCM (a) and GM (b) h: Height of an inner growth ring arc (measured), L: Length of the inner growth ring arc (measured), r: The missing radius (calculated), m: The distance by which the core misses the pith (chronological centre); arrow in Figure 2a shows perfect drilling direction ensuring the best match with annual rings, (Figure 2b is derived from Duncan 1989).

An additional software module (including export option) must be purchased to obtain each amplitude values of the device. But, in this study we used a free and easy way which allows exporting the data without purchasing any additional module. Charts of the device were transferred into ImageJ software and the data was obtained following the steps proposed by Icel and Guler (2016). All measurements were done in pixel then pixel values were calibrated at the end of the image analysis process. The data that belongs to the bark part was removed from the data set. Followed steps for transferring data to excel are given below:

1- Open F-Tools Pro

2- File –Open – Select File

3- Click Mirror and 5x zoom

4- Use one of the free print screen software such as "Gadwin PrintScreen" to take print screens as BMP or JPG file.

5- Repeat these steps for every single chart file and save them into the same folder.

6- Open Image J software.

7- Run the macro code (Icel and Guler 2016) (Seen Appendix)

8- The macro will ask a folder to proceed. Point out the folder where you saved image files.

9- Then it will ask to select beginning and ending of each chart.

10- At the end it will provide an excel file for each image.

In the literature, increasing slope of charts were corrected using different methods (Isik and Li 2003). In this study, the slopes of charts were corrected using a FTIR baseline software (Figure 3). This method is much easier than the previously proposed methods.

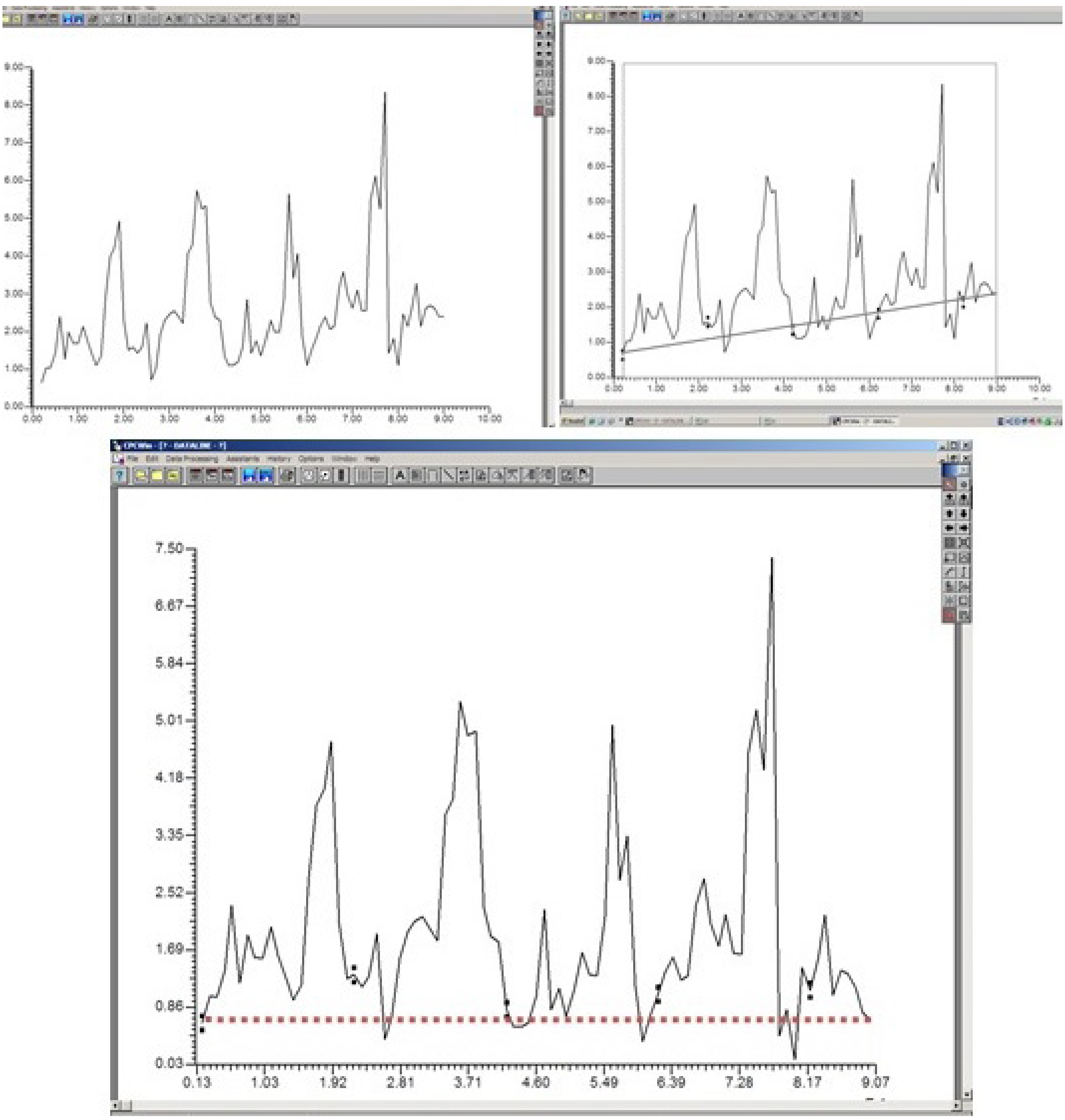

Figure 3: Correction of slope.

An x-ray densitometry dataset of author, which was validated at the Genobois laboratory, INRA, France, was employed for model estimations. A mass attenuation coefficient of 3,03 cm²/g for red pine (*Pinus brutia* Ten.) (Guller 2010) was applied to the formula provided below (Equation 1)(Bucur 2003). The wood density value used in this study was calculated as the average of the microdensity profiles.

$$p = \mu / \mu' \quad (1)$$

μ : The attenuation of an x-ray beam passing through the wood specimen

μ' : Mass attenuation coefficient

ρ: Density of sample

Statistical analysis

Least squares technique was used to obtain the best fitted model as mentioned in Miller (2006). The Equation 2 used for building the model was:

$$y = b + cA \pm e \quad (2)$$

Where:

y= Density (g/cm^3)

c= slope

A= amplitude

b= constant

e= error

Six subgroups based on positioning were tested using ANOVA. Duncan's multiple range test performed as post-hoc test. The linear model (subgroup 6th) was compared to x-ray densitometry results using a paired t-test on a randomly selected same-size subset of the data.

RESULTS AND DISCUSSION

Scattering diagram for amplitude and wood density for Sample Group 1 (trees sampled in the five different experimental sites, including trees at different ages) showed a statistically significant and moderately strong positive linear relation between wood density and amplitude data (Figure 4).

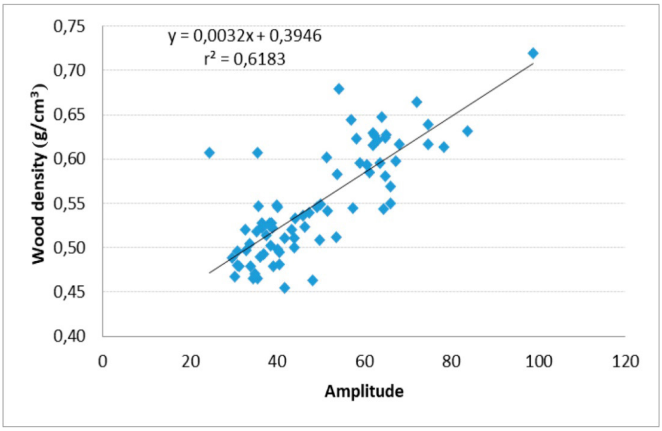

Figure 4: Scattering diagram for amplitude and wood density for the sample Group1 (Range of density:0,270 g/cm^3; coefficient of variation:11%).

For sample Group 2, in contrast to sample Group1, there was not any statistically significant linear relationship (Figure 5).

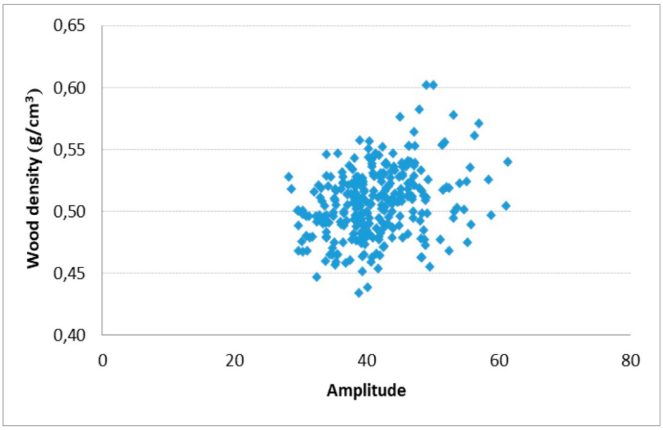

Figure 5: Scattering diagram for amplitude and wood density for the sample Group2 (Range of density:0,131 g/cm^3; coefficient of variation:8,5%).

In terms of mean wood density, there is no significant difference (p: 0,180 >0,05) among the six investigated data groups (The dataset to see drilling positioning effect) from the AK site. However, a statistically significant difference (p: 0,005 < 0,05) was observed for the device measurements (Table 2). Post Hoc test (Duncan) subsets for amplitude data are presented for each group (Table 3). Some statistical descriptives of density for six subgroups is given below (Table 4). Linear modelling between wood density and the device data were not statistically powerful for five of the six sub-groups from AK (Figure 6). Only sub-group 6th, which employed the geometric (GM) and Concentric Circles (CCM) correction methods for measurement positioning, exhibited an exceptional linear relation. The range of density variation for sub-group 6th (0,447-0,602) was wider than that of the other sub-groups, with a coefficient of variation of 0,07.

Table 2: ANOVA results for density and amplitude for six sub-group (AK site).

ANOVA						
		Sum of Squares	df	Mean Square	F	Sig.
x-ray density	Between Groups	0,006	5	0,001	1,531	0,18
	Within Groups	0,219	293	0,001		
	Total	0,224	298			
Amplitude	Between Groups	725,49	5	145,098	3,447	0,005
	Within Groups	12333,73	293	42,095		
	Total	13059,22	298			

Table 3: Duncan test results for amplitude.

Duncan a, b			
Sub-group of AK	N	Subset for alpha = 0,05	
		1	2
5	50	38,83	
1	50	38,98	
6	49	41,19	41,19
2	50		42,09
4	50		42,15
3	50		42,79
Sig.		0,09	0,27

Table 4: Some statistical descriptives of density for six subgroups (AK site).

Subgroup No	Range	Minimum	Maximum	cv (%)
1	0,093	0,454	0,547	4,8
2	0,126	0,452	0,578	5,5
3	0,102	0,459	0,561	5,1
4	0,117	0,434	0,551	4,3
5	0,119	0,439	0,558	5,2
6	0,155	0,447	0,602	7,1

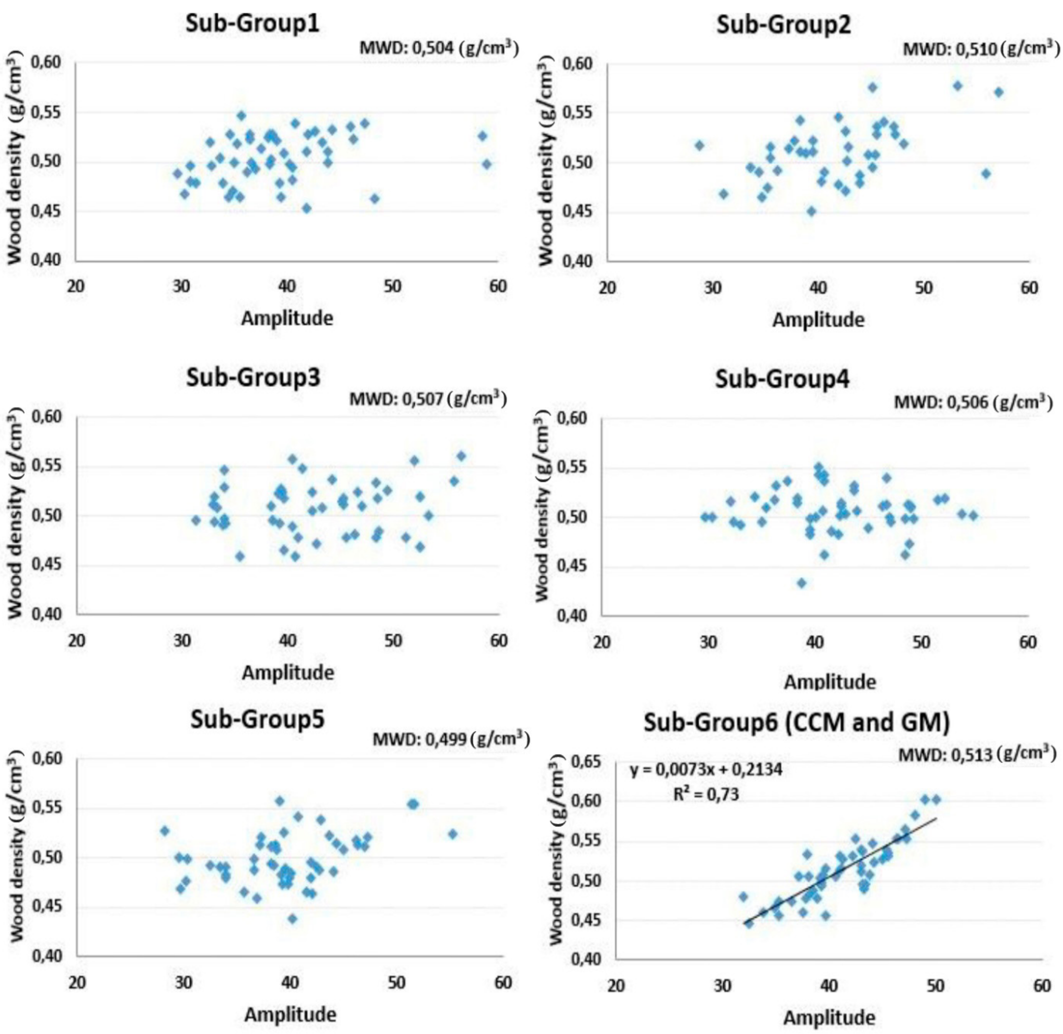

Figure 6: Data (Amplitude) and wood density relations for the six sub-group, MWD: Mean wood density (x-ray densitometry, for the same group).

Depending on ranking for density and amplitude values there is not mutual matching between the two columns, except the last two sub-group (Table 5). A trend is clearly seen that higher amplitude indicates higher density, and vice versa, if the density range becomes larger (Figure 4). Even though there was not a linear relationship between density and amplitude for the other group (Figure 5), of which the density range was low, it is remarkable that the lower mean amplitude indicates lower mean density for it. Indeed, in ranking for mean values of x-ray density and amplitude for subgroups the two low densities matched the two low amplitudes (Table 5).

Table 5: Ranking table for mean values of x-ray density and amplitude for subgroups.

Ranking for mean density (Sub-Group number)	Ranking for mean amplitude (Sub-Group number)
0,513 (6)	42,79 (3)
0,510 (2)	42,15 (4)
0,507 (3)	42,09 (2)
0,506 (4)	41,19 (6)
0,504 (1)	38,98 (1)
0,499 (5)	38,83 (5)

High correlation (with 0,927 correlation coefficient) was found between model (built by using the sub-group 6th data set) prediction and density values for the same trees obtained from x-ray densitometry. However, the results of paired sample t test (Table 6) did not reveal mutual matching at individual tree basis. The data obtained from x-ray densitometry was statistically different ($t=2,305$; $p=0,025<0,05$) from predicted density data at a 95% confidence level (Table 6). On the other hand, mean density value (0,514 g/cm^3) estimated from the model found close to mean density value (0,513 g/cm^3) obtained from x-ray densitometer for the sub-group 6th.

The difference between model prediction and x-ray densitometry is given below (Figure 7).

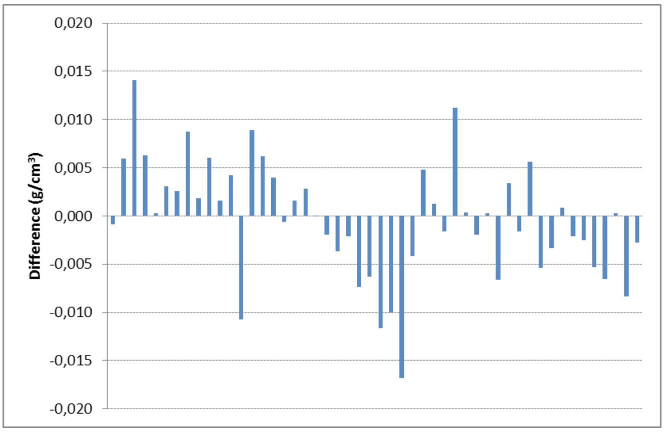

Figure 7: The numeric difference between the density estimates and the x-ray densitometry values of the same trees for sub-group 6(minus values indicate x-ray densitometer values are higher than model estimates) (The y-axis intervals were chosen small to increase visibility. Therefore, the visual differences in Figure 7 are perceived greater than the actual numerical differences).

Table 6: Paired sample t-test results between the model and x-ray densitometry results for the sub-group sixth.

Pair	Mean	Standard deviation	Standard error	t	df	P
density (x-ray)-density(model)	0,005	0,015	0,002	2,305	48	0,025

Different researcher reported moderate to high possibility for estimation of wood density with their model (varying r^2 values from 0,67 to 0,81) in controlled conditions (Faggiano *et al.* 2009, Acuña *et al.* 2011, Icel and Guler 2016). There are other results showing considerably low r^2 values for their linear models but, indicating that population mean density is better estimated than individual density in standing trees: Isik and Li (2003) for loblolly pine (*Pinus taeda* L.); Chantre and Rozenberg (1997) for douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco); Bouffier *et al.* (2008) for cluster pine (*Pinus pinaster* Aiton); Gwaze and Stevenson (2008) for short-leaf pine (*Pinus echinata* Mill.); Johnstone *et al.* (2011) for victorian eurabbie (*Eucalyptus globulus subsp. Pseudoglobulus* (Naudin) J.B.Kirkp.). Most of the literature on this method can be used to obtain general trends in the context of tree selection and that it can be used to estimate population mean density (Gantz 2002, Isik and Li 2003, Wang *et al.* 2003, Wang *et al.* 2005, Wang *et al.* 2008, Eckard 2007, Isik 2008, Eckard *et al.* 2010). There are many effective factors and variables related to trees, environment and device such as tree species, tree age, defects, resin content, resin pockets, heartwood-sapwood, juvenile wood, moisture content, annual ring structure, ring orientation, positioning of device, user experience, needle sharpness, air temperature etc. (Rowell and Konkol 1987, Zobel and Sprague 1998, Zobel 1992, Haygreen and Bowyer 1996, Treacy *et al.* 2000, Niemz *et al.* 2002, Ukrainetz and O'Neill 2010, Icel and Guler 2016). These factors possibly lead to differing results in literature. There is only few researches which were specifically focused on individual effects of these factors (Ukrainetz and O'Neill 2010, Sharapov *et al.* 2018). Operators can easily realign the drill by 10 degrees or more while drilling. Despite explicit instructions to maintain a steady position until the bit exits the stem, generally users could not keep their position especially when making multiple consecutive measurements on slopes.

The main advantage and purpose of the method and such device's usage is to be relatively less destructive for standing trees and more practical and cost effective to estimate density without taking any increment core. The most succeed linear model (Figure 6) is obtained by support of positioning methods, and increment cores. Therefore, the model built by using the subgroup 6th data, did not show mutual matching for a random test group due to the way of obtaining data, and even though its considerably high r^2 value, impracticable for individual estimates. Depending on our experience and results, user experience/care solely is not sufficient for correctly positioning (perpendicular to rings) drilling path on standing trees while working such devices. Amplitude values obtained by such device current form can be used to broadly categorize trees as having either low or high density only if there is a high coefficient of variation (over 10 %) among trees. The device's current capabilities are insufficient for precisely determining the density of individual standing trees.

CONCLUSIONS

If there are significant variations for tree density of a population (over 10 %), regardless of age or other factors, linear modeling can provide a moderate accurate estimate of the population's mean density.

In this paper, only modelling for one group of trees, which we used the CCM and GM methods to establish the drilling place, showed moderate success for estimating density. The group has also slightly greater density variation than other subgroups. That means, for smaller populations (i.e. around 50 trees for the study), which have low density variation, it is not likely to have statistically successful models even for mean density of population by using amplitude values obtained with current way.

Following a more perpendicular path to rings improved the numerical results especially for mean value and some individual estimates, but the paired sample t test did not show statistically satisfactory mutual matching for all trees of the group. The data obtained from x-ray densitometry was statistically different than model estimates ($t=2,305$; $p=0,025<0,05$) at a 95% confidence level. Improving drilling paths can yield acceptable estimates for practical forestry applications. However, this method should not be considered a viable alternative to other methods for individual estimates. Depending on literature knowledge and current experience, theoretically and practically there is a clear relation between density and drilling resistance of wood. Yet, there are many factors affecting the density-amplitude relations, and currently there is not enough literature to easily separate each individual effect. The current results are important to be able to elucidate individual effect of drilling direction and make a valuable contribution to partly explain why previous models were not powerful enough.

There has been a need for a non-destructive method working without increment core collection for standing trees especially for practical forestry, and depending on cumulative literature knowledge drilling resistance method seems still a probable candidate if its technological limitations would be solved. As a connecting conclusion from the literature to current results, efficient selection of pine trees by estimating mean wood density with the method would be possible if the requirements are met. However, the current results and experience showed that to meet the requirements and to have more powerful linear models, such devices primarily should be improved by practical and cheap hardware / software for positioning of device to have best drilling path.

Authorship contributions

B.I.: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, validation of model, resources, visualization, writing-original draft.

Conflict of interest

The author declares that previous publications cited in this manuscript may contain misused references to the trademarked term ‘Resistograph’ due to historical disputes unrelated to the present study. The author has no current commercial affiliation with the manufacturers involved.

Acknowledgements

This research was supported by The Scientific and Technological Research Council of Türkiye (TÜBİTAK), Project No. 110-O-560. The author thanks Philippe Rosenberg and the Genobois Laboratory (INRA, France) for technical assistance in validating the x-ray densitometry dataset. Additional analyses not included in the original project report were conducted subsequently for the purpose of this publication.

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