The Agreement in Accuracy between Tomograms, Resistograms, and the Actual Condition of the Wood from Lime Trees Harvested from Cities

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The internal quality of the wood is one of the main factors affecting the stability of trees, and it has always been of great interest to science and practice. For this reason, the present study aims to compare the results obtained by wood tomograms with those of resistance to drilling and the visual appearance after cutting a slice with a chain-saw, both to evaluate the presence and dimensions of the inside defects, and also to evaluate the irregularities of the wood structure. Round pieces of lime wood harvested from public areas were used for comparison by taking sound tomograms, followed by taking resistograms on two perpendicular directions at the same level. The results showed that internal wood defects are not always the ones that lead to reduced speeds of sound propagation through the wood. In addition, there were instances in which changes in the internal structure of the wood led to improperly colored tomograms, namely the sections characterizing the point of insertion of a thick branch in the trunk, where the tomograms indicated low speeds of sound transfer through the wood in the stem and high speeds in the wood of the branch.

DOI: 10.15376/biores.18.1.1757-1779

Keywords: Sound tomograms; Power drill machine; Relative resistance to drilling; Lime trees; Wood quality; Internal defects

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INTRODUCTION

Green areas of cities, parks, and public gardens are enjoyed by the community (Kirkpatrick *et al.* 2012), so those responsible for these areas aim to obtain as many varieties as possible of shrubs and trees, with different shapes and habits (Camacho-Cervantes *et al.* 2014).

Regardless of the area in which they are located, during their existence, the trees change their internal structure and shape, either due to the natural causes imposed by the stages of development or environmental conditions, or due to anthropogenic causes such as fires or pruning (Musat *et al.* 2020). The anthropogenic actions mostly occur in trees from cities, whose growth and development are influenced either by pruning of crowns (Seifert *et al.* 2010) or by reducing the space for root development, particularly in the case of street trees because they are forced to develop their root system among the cables and pipes in the soil, near unsuitable materials (Saebø *et al.* 2005; Bartens *et al.* 2010), or soils poor in nutrients (Parascan and Danciu 2001).

As any human intervention in nature does not remain without consequences (Nimară *et al.* 1964; Suciu 1975), trees also react through their own adaptation processes.

Sometimes the anthropogenic actions are so severe that they affect the integrity and even the stability of the trees, especially in the case of trees located in the cities, near the road, which are cut extremely intensively. In contrast to trees from forests managed for production, whose management is aimed at getting high quality wood for various industrial uses (Sandoz and Lorin 1996; Garrett 1997; Wang *et al.* 2007; Mu *et al.* 2010; Du *et al.* 2015; Qu *et al.* 2020; Lin and Wu 2013; Sandak *et al.* 2020), for urban trees the main aim is to maintain their vitality, integrity, and stability for as long as possible (Kirkpatrick *et al.* 2012; Camacho-Cervantes *et al.* 2014; Sandoz and Lorin 1996; Deflorio *et al.* 2008; Wang *et al.* 2009). Initially, the condition of a tree and its maintenance or removal was decided by a single person, who visually evaluated it (van Wassenaer and Richardson 2009). Then, the verification of the internal quality of wood in standing trees became a long-term concern (Roughton 1982; Bucur 1986; Bucur 2003; Alvers *et al.* 2015). As a result, a series of tree condition assessment devices were developed, some of which are highly invasive, some are less invasive, and the rest are considered non-invasive (Catena 2004; Deflorio *et al.* 2008; van Wassenaer and Richardson 2009).

A number of tools have been developed to evaluate the integrity of wood in standing trees based on the principle of wave propagation in solid environments (Wang *et al.* 2007; Lin *et al.* 2011; Lin and Wu 2013; Wang 2013; Li *et al.* 2014; Alves *et al.* 2015; Bouchet and Danneau 2017), namely those using sounds (Deflorio *et al.* 2008; Rohanova 2009; Brancheriau *et al.* 2012) and ultrasounds (Tomikawa *et al.*1986; Sandoz and Lorin 1996; Garrett 1997; Martinis *et al.* 2004; Alves *et al.* 2015). By such determinations, one can get images of the analyzed sections (Liang and Fu 2012; Feng *et al.* 2014; Li *et al.* 2014; Alves *et al.* 2015; Du *et al.*2015), either by using various computational algorithms (Sandoz and Lorin 1996; Du *et al.* 2015) or software provided by the tool's producers (Rinn 2014).

Sound is a wave that propagates through compression and expansion of the environment in which it develops (Beldeanu 2008; Bouchet and Danneau 2017). Knowing the speed of sound through a material is important because it can provide clues about the nature and purity of the material (Bouchet and Danneau 2017). In the case of wood, as a solid material, this principle is used in sound analysis with the aim of detecting hidden irregularities located inside the wood (Garrett 1997; van Wassenaer and Richardson 2009; Ellis 2014; Alves *et al.* 2015; Du *et al.* 2015).

Acoustic wood quality assessment methods can be applied both to standing trees (Garrett 1997; Martinis *et al.* 2004; Lin *et al.* 2008; Lindström *et al.* 2009; Feng *et al.* 2014) and harvested round wood (Sandoz and Lorin 1996; Rohanova 2009). The main difference in the application of methods would be that of different direction in which the sound is propagated (Fu 2005; Beldeanu 2008; Kazemi *et al.* 2009). As such, in trees the acoustic method can be used only at the level of some cross-sections (Martinis *et al.* 2004; Wang *et al.* 2007; van Wassenaer 2010; Feng *et al.* 2014; Li *et al.* 2014; Musat *et al.* 2014; Rinn 2014) located on the stem, branches, or even roots (Sandoz and Lorin 1996; Malinovski *et al.* 2016), while for harvested stems or logs, the method can be used also parallel to the fibers, in the longitudinal plane (Lear 2005; Rohanova 2009; Wang and Carter 2015).

The speed of sound propagation on the direction of the fibers is species variant, being 3 to 5 times faster than the speed of propagation perpendicular to the fibers (Beldeanu 2008), and it depends on the angle between the emitter-receiver sensor pairs (Feng *et al.* 2014; Li *et al.* 2014; Du *et al.* 2015). This is because the sound wave must cross all annual rings, earlywood and latewood, wider or narrower rings (Sandoz and Lorin 1996; Beaulieu and Dutilleul 2019). In addition, there are variations in propagation speed occurring in the same species. This is common in trees of the same species that have developed in contrasting environments, which caused an impact on the internal structure of the wood (Beldeanu 2008; Lindström *et al.* 2009; Dinulica *et al.* 2020). In particular, such changes affect the density of wood, which is known to affect the speed of sound propagation (Tarasiuk *et al.* 2007; Wang *et al.* 2007; Beldeanu 2008; Deflorio *et al.* 2008; Liang and Fu 2012; Dinulica *et al.* 2016; Bouchet and Danneau 2017), and which increases proportionally to the wood density. In addition, the anisotropy of wood, as one of its main characteristics (Beldeanu 2008; Feng *et al.* 2014; Du *et al.* 2015), produces variation in characteristics such as the mechanical and physical behavior across its mass (Lunguleasa 2004; Leboucher2014; Beaulieu and Dutilleul 2019).

When some internal defects are present, they affect the speed of sound propagation in wood (Sandoz and Lorin 1996; Ross *et al.* 1998; Ross and De Groot 1998; Martinis *et al.* 2004; Wang 2013; Wu *et al.* 2018; Moravcki *et al.* 2021), providing clues about the internal structure. However, the speed of sound propagation is influenced by a lot of factors, of which not all could be seen as defects, *i.e.*, factors that do not affect the integrity of wood.

Because acoustic analysis does not indicate the type of defect or its exact extent (Deflorio *et al.* 2008; Feng *et al.* 2014), and by doing so, it either overestimates (Wang *et al.* 2009) or underestimates (Martinis *et al.* 2004; Liang and Fu 2012), it is necessary to increase the number of used sensors (Divos and Divos 2005; Wang *et al.* 2007; Wunder *et al.* 2013; Du *et al.* 2015) or to carry on additional analyses (Tarasiuk *et al.* 2007; Siegert 2013; Feng *et al.* 2014) with the aim to determine the type of defect and its extent, and to evaluate its impact on the stability of the trees (Siegert 2013). For instance, it is accepted that the risks become important in case of defects or degradations that affect more than 60% of the analyzed diameter (Sandoz and Lorin 1996).

Due to the structural changes that some natural irregularities of the wood (forking, knots - Balleux 2004; Budakci and Cinar 2004; Alves *et al.* 2015) or defects (Lunguleasa 2004; Beldeanu 2008; Feng *et al.* 2014; Du *et al.* 2015; Du *et al.* 2018) have on the stability of trees, and the important role that trees are playing in public areas (Saebø *et al.* 2005; Kirkpatrick *et al.* 2012; Troxel*et al.* 2013; Camacho-Cervantes *et al.* 2014), it remains particularly important to periodically evaluate the internal quality of standing trees (Proto *et al.* 2020).

The goal of this work was to evaluate the agreement between sound tomograms and the true status of the wood, in the case of lime trees, to evaluate both the inside defects and the irregularities of the wood structure. The following objectives were set for this study: i) to compare the agreement between the sound tomograms and the true status of the wood; ii) to compare the sound tomograms with the diagrams with the relative resistance to drilling; and iii) to check whether the acoustic tomograph could identify the irregularities inside the wood.

EXPERIMENTAL

Field sampling was carried out at one of the teaching facilities of the Faculty of Silviculture and Forest Engineering of the Transilvania University of Brasov, in the spring. The determinations were made on lime round wood, at natural moisture, because the trees were harvested in the same week, a few days earlier. The choice of this species was based on the statements from the literature (Saebø *et al.* 2005; David 2011; Musat *et al.* 2014), according to which *Tilia* species are very common in the cities, and the characteristics of the wood are different compared to those of hardwood species.

As specialists (Tarasiuk *et al.* 2007; Feng *et al.* 2014) recommend the use of different methods for the correct identification of defects and their extension, the working methodology first involved performing analyzes by the means of Arbotom® Sonic Tomograph (Rinntech – Fig. 1a), followed by checking the relative resistance of wood to drilling (Fig. 1b) on two perpendicular directions, which was done by the IML Resi F-500S PowerDrill® and, finally, by extracting wood samples in the form of discs at each analyzed level by the use of a motor chain-saw (Fig. 1c). To compare the results with the true status of the wood, each newly created surface was photographed for further analysis at the office.

(a) **(b)** **(c)**

Fig. 1. The field sampling: a) the sensors were placed around the wood piece for acoustic analyses; b) the measurements were made by a wood drilling machine; c) the cross-cut for evaluating the true status of the wood

An Arbotom®–Rinntech Sonic Tomograph was used to measure the sound propagation. Measurements were done at the bottom/end, and then spaced at 50 cm levels, in directions perpendicular to the wood fibers. Measurements involved fixing the sensors on the circumference of the logs, with the help of special steel nails. The first piece was intended to capture the effect that defects may have on the speed of sound propagation. Taking into account the recommendations from the literature (Divos and Divos 2005; Karlinasari *et al.* 2011; Li *et al.* 2014; Rinn 2014), the number of sensors was chosen according to the diameter and complexity of the cross sections at the analyzed levels, being used between 6 and 18 sensors.

After placing the sensors, creating and verifying the connection between the sensors and the Arbotom® soft installed on a laptop, the diameter and the position of each sensor on the circumference were entered in the program (Fig. 2a), including the deviations from the circular shape, when necessary. Measurements were done by inducing sound pulses by successive actuation of the sensors. During the measurements, each sensor acted as a transmitter and receiver (Alves *et al.* 2015; Proto *et al.* 2020; Morovcik *et al.* 2021). Thus, starting with sensor number 1, each sensor was hit with a metal hammer 7 times to generate sound waves that propagated to all other sensors, which acted as receivers. The number of pulses was chosen according to the ambient noise (Tarasiuk *et al.* 2007; Musat *et al.* 2020) and based on the recommendations of the manufacturer (http://rinntech.de, 5 to 10 pulses for each transmitter, and the number of required pulses increasing with the noise level in the area). When the wave from the transmitter reaches a receiver, the tomograph program automatically calculates the speed of sound propagation through the wood. During the measurements, the value of the transmission errors was permanently monitored so as to be less than 3%, as specified in the literature (Wang *et al.* 2007).

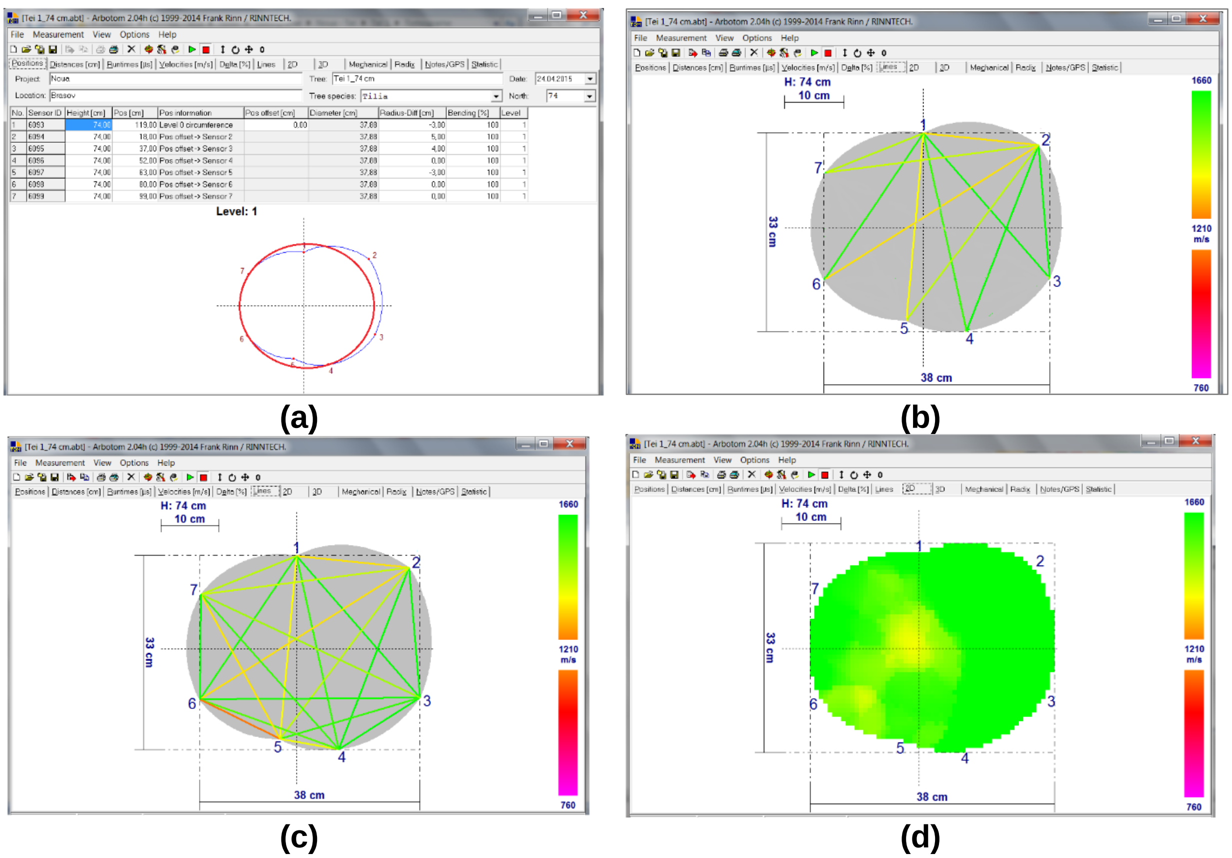


Fig. 2. The software of Arbotom® tomograph: a) Rectifying the circumference of the transverse section of the round wood: with the red line the initial shape, and with blue line the rectified profile; b) The lines drawn by the specific soft of the sonic tomograph between the transmitters sensors (1 and 2) and the receivers (other sensors); c) The connections between the pairs transmitter-receiver sensors; d) The tomogram reconstructed based on the average speed of sound propagation through the wood

Based on several propagation speeds recorded between the transmitter and the receivers, the tomograph program calculates an average speed according to which it draws a link line between each transmitter-receiver pair (Fig. 2b). As all the sensors play the role of transmitters and receivers, for a given section the program builds a set of connecting lines between the sensors (Fig. 2c). Based on these speeds, the program constructs a colored tomographic image (Wu *et al.* 2018), which indicates/segments by a color palette. The healthy wood or areas without internal irregularities are where the wave can be transmitted faster (http://au.ictinternational.com/casestudies/example-arbotom-raport), which is in contrast to areas having rot, degradation, or mechanically damaged wood (http://ictinternational.com/casestudies/detecting-fungal-decay-in-palm-stems-by-resistance-drilling), (Fig. 2d).

Measurement of the drilling resistances was done using an IML Resi F-500S PowerDrill®, which enables the penetration of the drill into the wood at a constant pace, making it possible to get the variation in resistance as a function of penetration depth. The device was equipped with a drill of 50 cm in length and 3 mm in diameter (https://www.iml-service.com/product/iml-powerdrill/), which allowed the penetration of the entire section.

For each section at which a tomogram was taken, two measurements were done with the wood driller machine. The directions of measurement were always north-south and east-west facing, where the north direction corresponded to the position of the first sensor placed on the trunk to measure the speed.

Regarding the values of the relative resistance at drilling, it was assumed that the wood was healthy if on the diagram the values of resistance were uniform, without significant sudden oscillations (Rinn 1994; Proto *et al.* 2020) or if the resistances increased progressively from the periphery of the stem towards its center. In contrast, areas with rot are commonly identified by a sudden decrease in resistance, which tends to 0% (Wu *et al.* 2018), a behavior which is characteristic of parts with internal holes (hollows). In the same way, areas with wood in various stages of degradation or areas with structural irregularities, characterized by sudden and short-lived oscillations of relative resistance compared to those of the surrounding wood, can also be detected.

Following the analyses regarding the relative resistance at drilling, the round wood pieces were cross-cut by using a Husqvarna chain-saw, which was handled by a qualified operator. Each newly created surface was photographed using a photo camera Sony, model DSLR-A200k with lens SAL 18…70 mm. The present measurements also attempted to check whether the acoustic method can recognize the small defects inside the wood. Even if the defects smaller the 1 cm can be seen by the photo camera and by visual evaluation, these small defects cannot influence the stability of the entire tree.

The images were intended to reflect the true status of the wood inside the stem and were saved in relation to the number of wood samples and level analyzed, so that comparisons between tomograms, resistograms, and photographs could be made later. Probes and photographs of the sections were taken immediately after the measurements done with the sonic tomograph and the wood drill machine, so as to avoid the mistakes of association that might affect the interpretation of the results.

RESULTS AND DISCUSSION

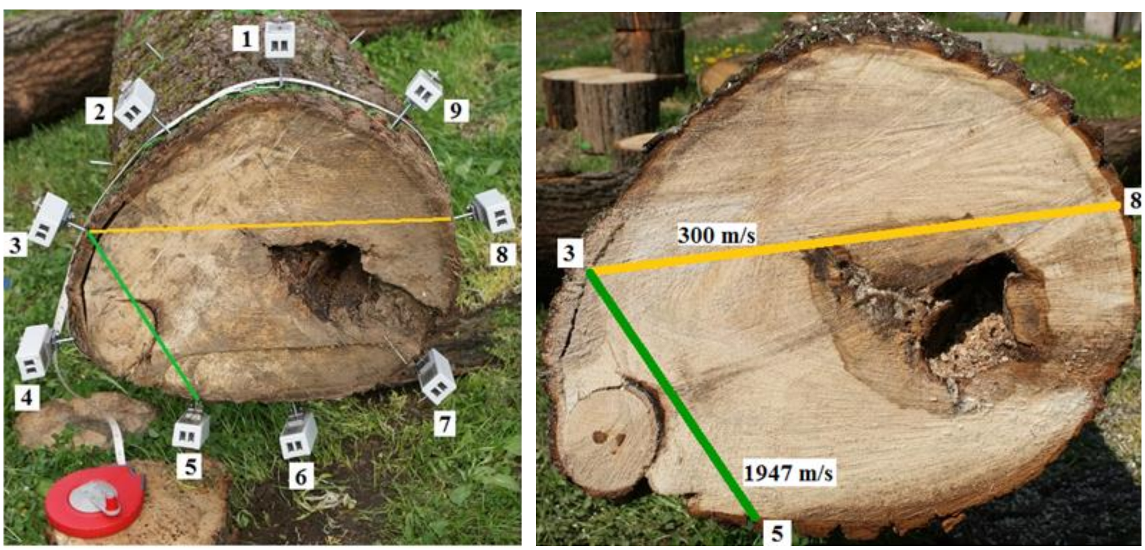
Speed of Propagation and Resistance to Penetration

The measurements done by the tomograph resulted in a total of 31 tomograms and 62 resistograms, which were compared to the real condition of the wood, visible from the sections made with the mechanical chain-saw at each level.

The sounds were not always transmitted between all pairs of sensors (transmitter - receiver), so that the total number of formed links was less than the number of possible links. Such situations were identified only at the second (at level of 410 cm, between sensors pair 5-6 and 6-5) and the third piece of wood, at the level of 10 cm (sensors pair 5-6 and 6-5) and at 210 cm, between the sensors 3-4 and 4-3. This problem was observed also by other researchers (Du *et al.* 2015; Du *et al.* 2018), who mentioned that the accuracy of the tomograms near the sensors is significantly lower than that inside the trunk.

The results indicated that the highest share (73 to 94%) was of speeds between 1001 and 1500 m/s. At a first glance, this does not point out special problems since the literature sets a reference speed of 1400 m/s for lime wood (Sandoz and Lorin 1996). In dried healthy lime wood, the speed in the longitudinal direction is 3700 m/s (Beldeanu 1999; Beldeanu 2008); the same sources (Beldeanu 1999; Beldeanu 2008) also claim that the speed of sound perpendicular to the fibers is reduced by 3 to 5 times compared to that along the fibers.

However, there were large variations in the minimum values recorded, starting from 283 m/s (section from 56 cm - the first piece of wood), continuing to 300 m/s (section from 10 cm of the second piece), and reaching 1136 m/s (the 110 cm section of the third piece). Comparing the minimum values with the tomograms and the true status of the wood, only some of these values can be attributed to serious defects located inside the wood. In the second piece located at the level of 10 cm from the thick end of the stem, two defects were present, namely a hollow and a knot, and the minimum speed recorded on the direction of sensors 8-3 is justified by the presence of a rotten area in various stages of development (Fig. 3).



(a) (b)

Fig. 3. Extreme values of the speed of sound propagation through wood: a) location of the sensors at the analyzed section; b) directions of sounds propagation

If the wood is healthy, then the wave can pass in a straight line from the transmitter to the receiver (Feng *et al.* 2014; Rinn 2014), while if the tree has rot at the analyzed level, the sound wave must bypass the affected area (Garrett 1997; Lin and Wu 2013). Even if the path of the wave is not clear in degraded wood, the speed of propagation of the sound is much slower than in wood without defects (Lin and Wu 2013; Wang 2013; Rinn 2014). Compared to all the other low values of the speeds, sometimes they have nothing to do with internal defects, as the wood is healthy. However, in the tangential direction, the propagation velocities are lower than those on the radial direction (Beldeanu 2008; Lin *et al.* 2008; Kazemi *et al.* 2009; Liang *et al.* 2010; Feng *et al.* 2014). In addition, the sections in which these values were recorded have an oval shape, which further supports the claims that the propagation velocities are closely related to the anatomical structure of the wood (Feng *et al.* 2014; Alves *et al.* 2015) and that an uneven width of the annual rings influences the density of the wood (Filipovici 1964; Sandoz and Lorin 1996; Beldeanu 2008).

Comparison of Tomograms with the Real State of the Wood at the Analyzed Levels

By comparing the tomograms with the newly created sections at the analyzed levels, it was found that in some cases the reconstructed image correctly illustrated the real condition of the wood (Figs. 4 through 7). This happened when the wood at the level of the analyzed section was healthy and did not show structural unevenness, which was observed also from the diagrams with the relative resistance to drill.

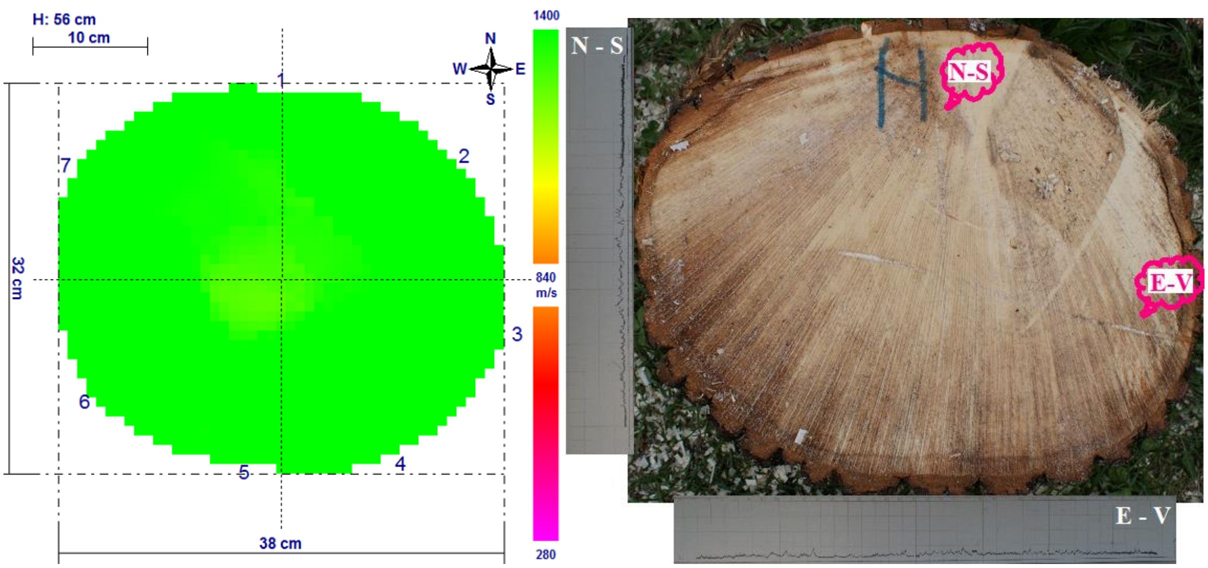


Fig. 4. The results from the level of 56 cm of the first piece of lime

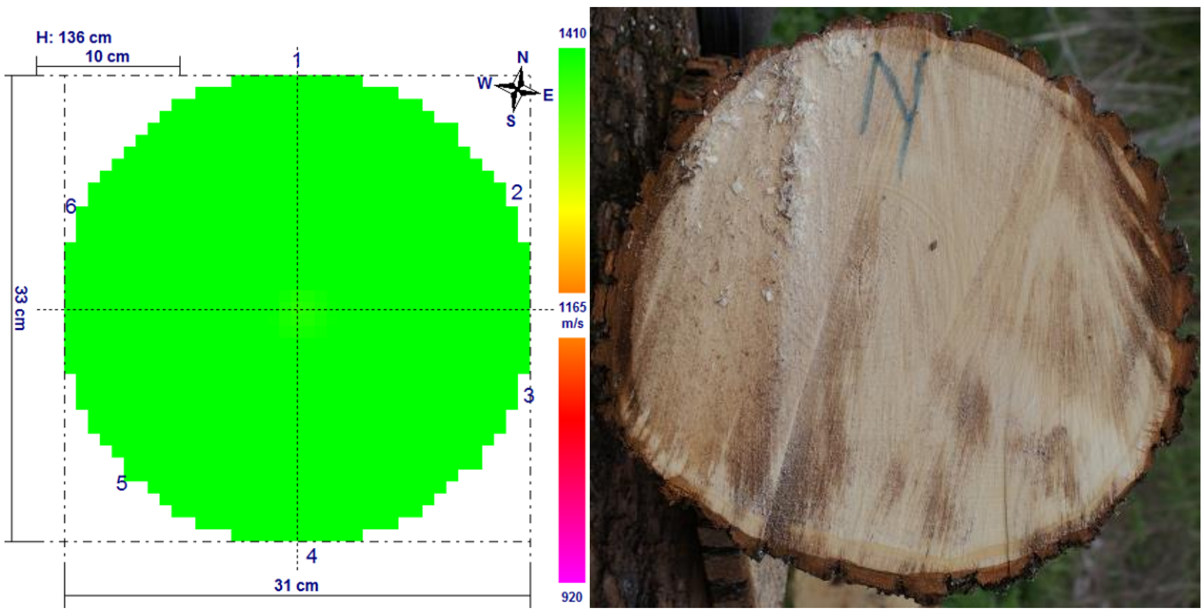


Fig. 5. The results from the level of 136 cm of the first piece of lime

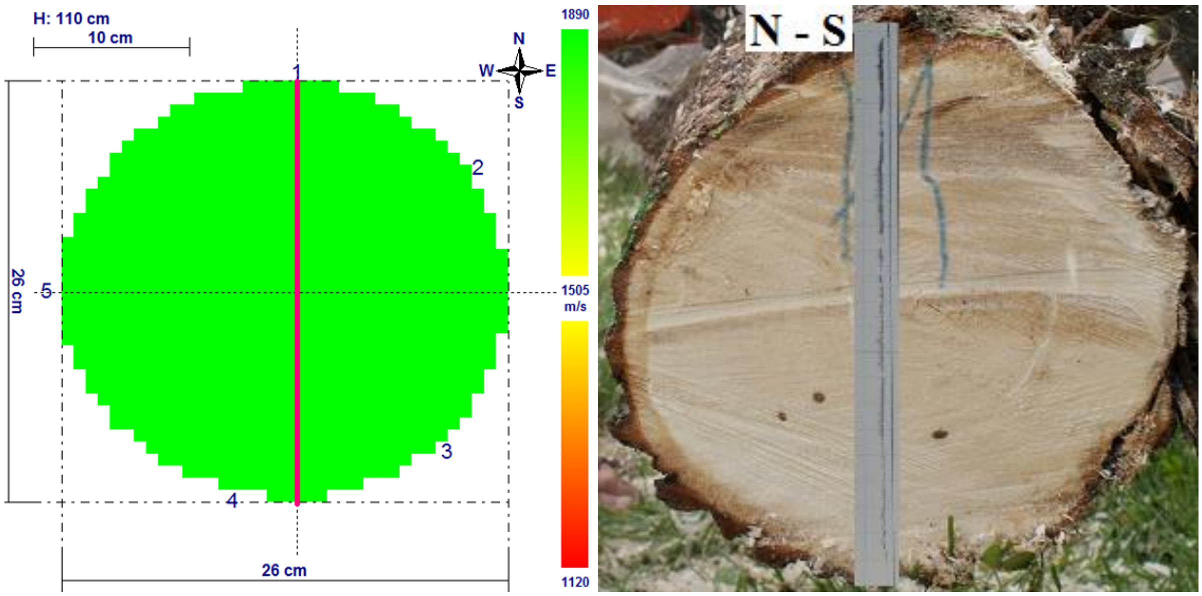


Fig. 6. The results from the level of 110 cm of the third piece of lime

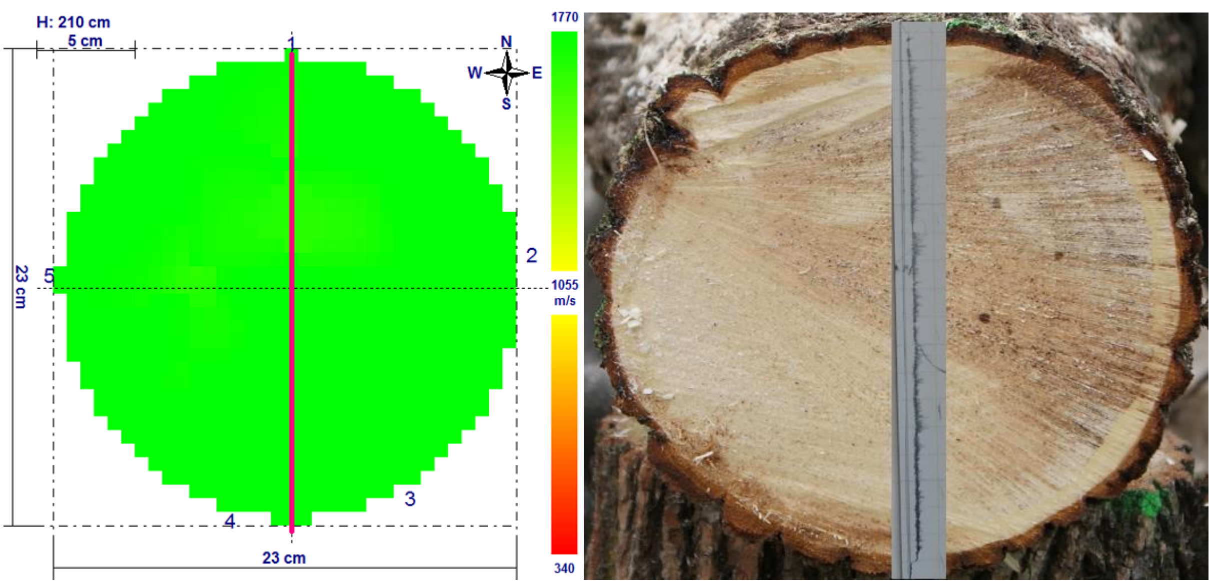


Fig. 7. The results from the level of 210 cm of the third piece of lime

In some cases (Figs. 8 and 9), tomograms illustrated lower speeds of sound transfer through wood on the tomographic images, even if the actual condition of the wood indicated healthy wood. These two figures support, once again, the influence of the structural characteristics of wood on the speed of sound propagation (Sandoz and Lorin 1996; Lindström *et al.* 2009) and the fact that the tomograph cannot distinguish between the wood with defects and healthy wood, but with structural irregularities. The areas characterized by lower speeds were located either in the central area of the stem (Fig. 8) or in its lateral part (Fig. 9). The presence of wider annual rings was noticed in some sections, corresponding either to more favorable climatic conditions in the development of the tree (Rinn 1988; Beldeanu 1999; Beldeanu 2008), or to the local conditions of tree growth. These wider annual rings suppose a different proportion of early and latewood (Filipovici 1964; Beldeanu 1999; Beldeanu 2008), which influences the wood density in the area

(Nicolotti *et al.* 2003; Lin *et al.* 2008; Liang and Fu 2012; Feng *et al.* 2014; Li *et al.* 2014) and, finally, the speed of sound propagation (Sandoz and Lorin 1996; Wang *et al.* 2007; Leboucher 2014).

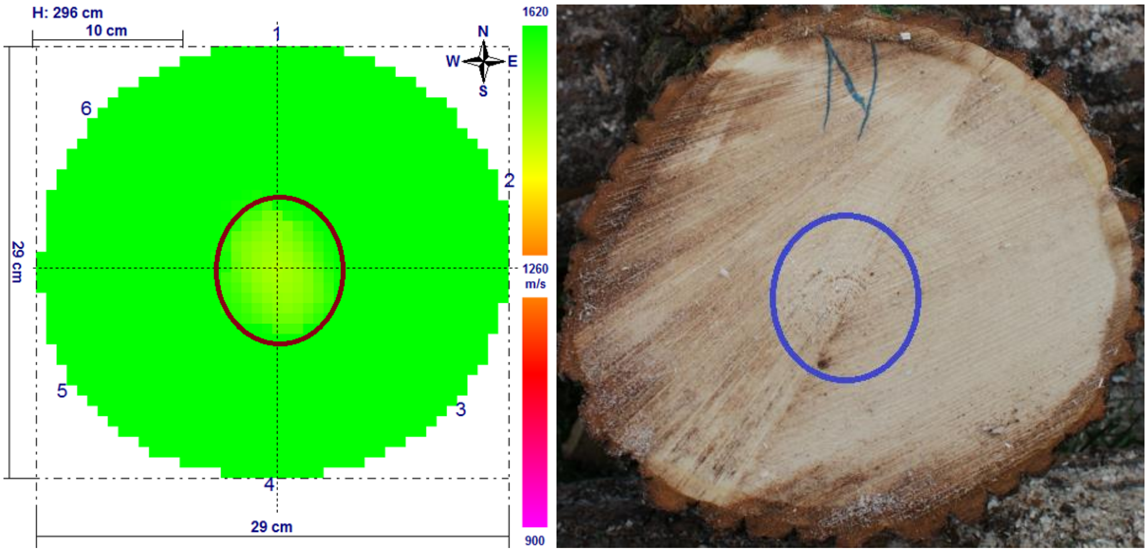


Fig. 8. The influence of wood density from the center of the trunk on the sound speeds

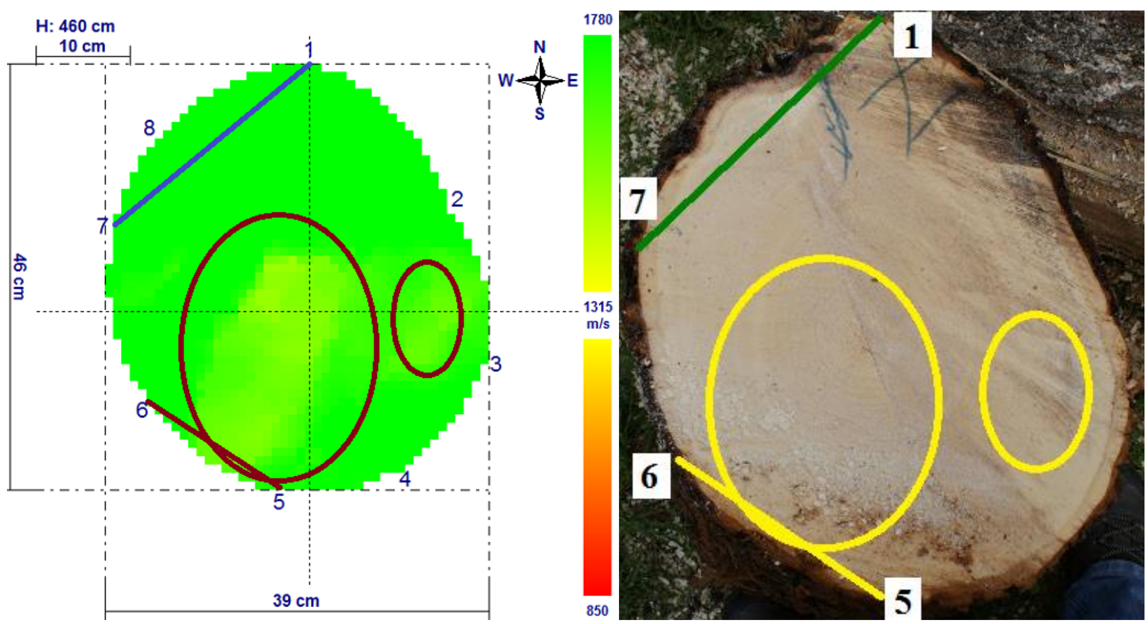


Fig. 9. Speeds of sound propagation through a portion with wide annual rings

The comparative analysis of the tomograms with the visual appearance after cutting a slice with a chain-saw showed that some small defects located inside the stem were not evident in the tomogram (Figs. 10 through 14), which is consistent with the results of Martinis *et al.* (2004), who stated that gaps of 1 to 2 cm in diameter are difficult to detect through an acoustic method. This is somewhat supported, on the one hand, by the small size of the defects, but also by the fact that, due to their size, these defects can be situated in between the paths of speed propagation or can be traversed only in one direction by the waves (Proto *et al.* 2020), which does not significantly influence the propagation speeds constructed by the tomogram. In this regard, Wang *et al.* (2007) point out that an unidirectional wave can only detect inner rot if it occupies more than 20% of the total area covered by that wave.

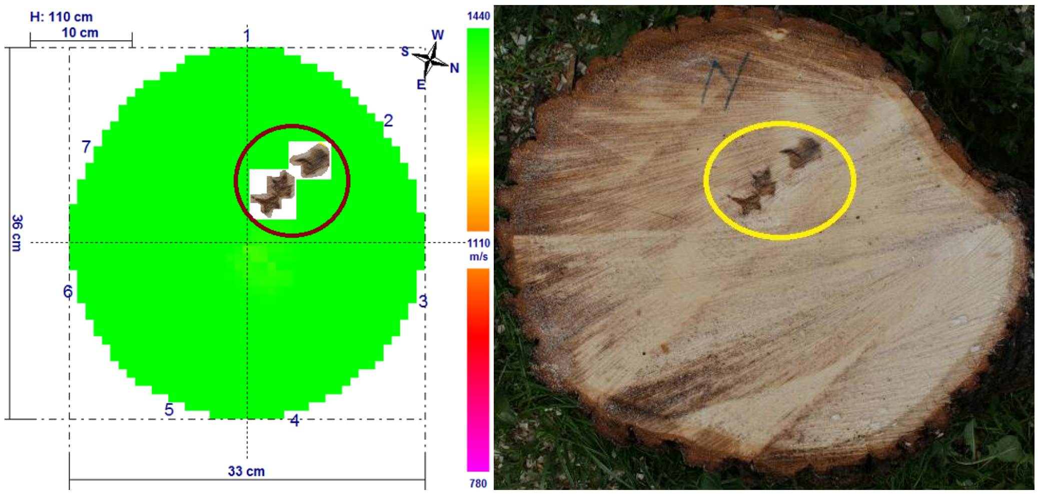


Fig. 10. Tomogram and section from 110 cm to the first piece of lime

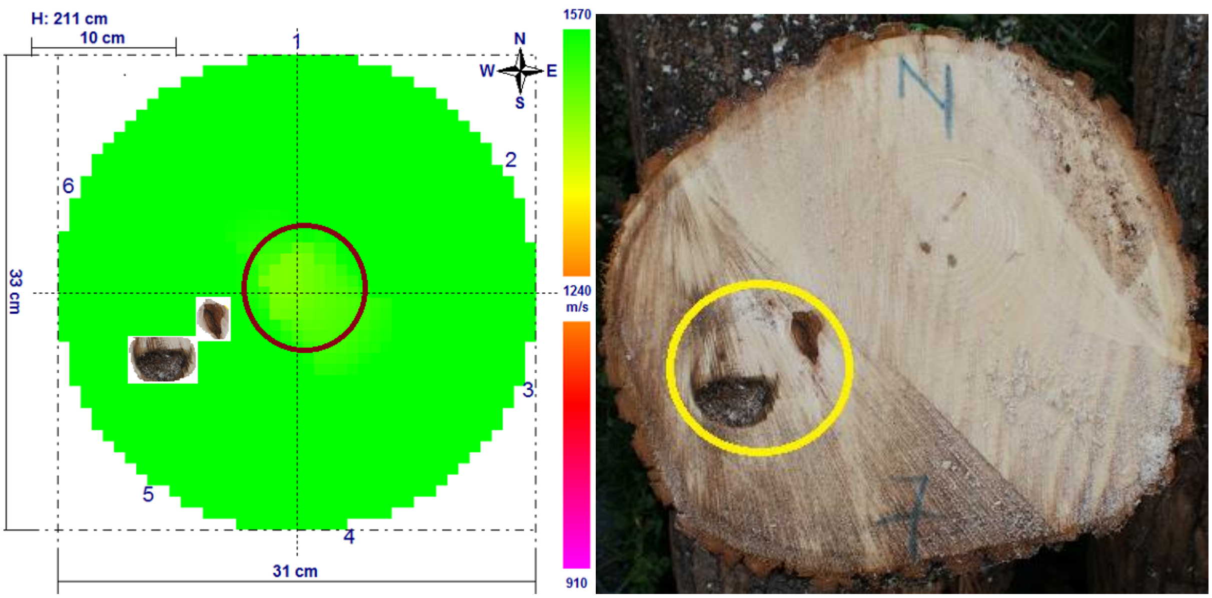


Fig. 11. Tomogram and section from 211 cm to the first piece of lime

These small defects, which do not pose a danger to the stability of the tree, are not the main objective of investigating the internal quality of wood by sound, as the method was designed to determine the properties of wood, its modulus of elasticity (Sandoz and Lorin 1996; Feng *et al.* 2014; Alves *et al.* 2015; Du *et al.* 2015), and, in particular, to detect inner rot (Brancheriau *et al.* 2008) and other defects that involve the destruction of the anatomical structure of the wood and the decrease of resistance (Martinis *et al.* 2004; Lin and Wu 2013; Ostrovsky *et al.* 2017).

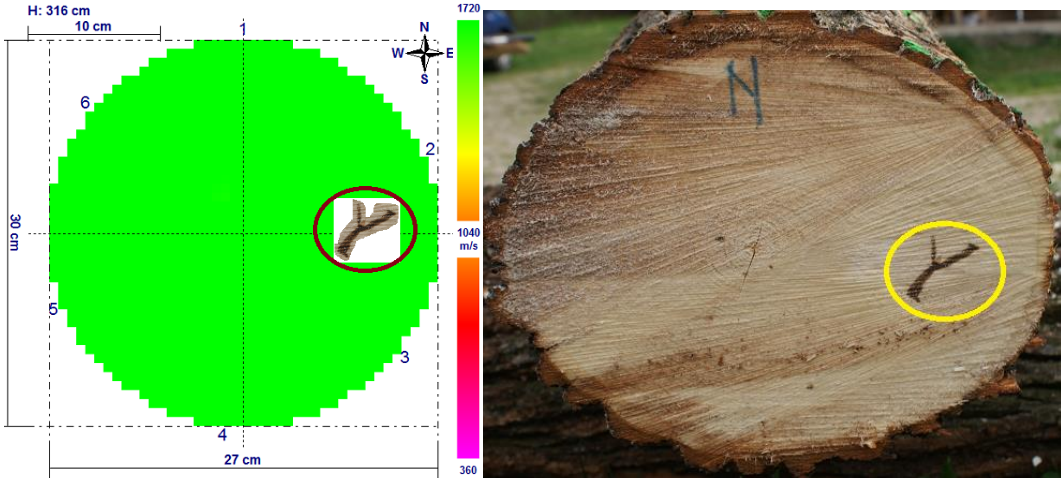


Fig. 12. Tomogram and section from 316 cm to the first piece of lime

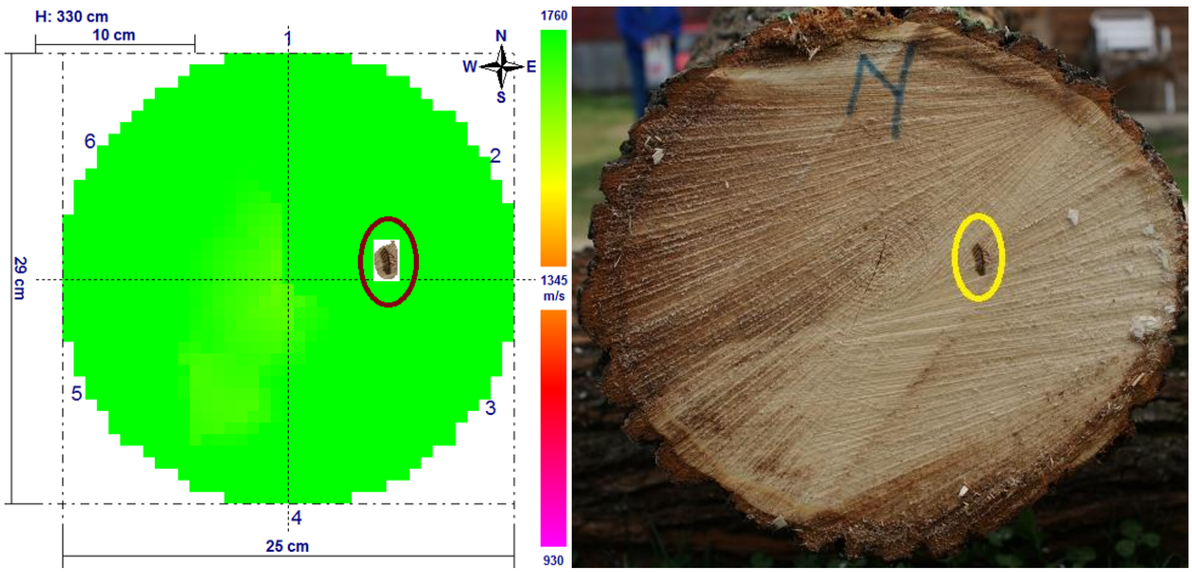


Fig. 13. Tomogram and section from 330 cm to the first piece of lime

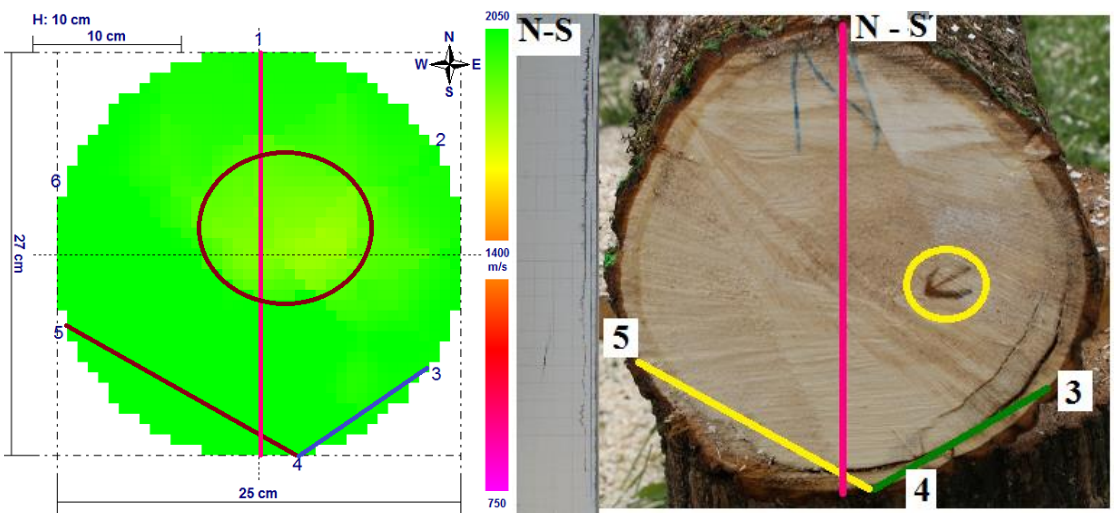


Fig. 14. Failure to recognize the knot on the 10 cm section of the third piece of wood

Unlike the tomograph, the wood drilling machine provides information on the change in relative resistance to drilling when the direction of the investigation also involves crossing these small defects, a behavior which is highlighted in Figs. 15 and 16.

The opinions on the use of power drill machine remain divided, with some considering the method to be highly invasive (Deflorio *et al.* 2008), while others considering it non-invasive (Catena 2004), or even having very little implication on further tree development (Wang and Allison 2008; Allison and Wand 2015). However, the use of the wood drilling machine to determine the internal properties of wood remains a method that provides more accurate details about the internal defects, even if these results could be considered local ones, and related only to the drilling direction (Rinn 1988; Rinn 1994). The method is recommended as a method of testing defects that are not clearly established (as type and extent) by other methods (Martinis *et al.* 2014; Wu *et al.* 2018).

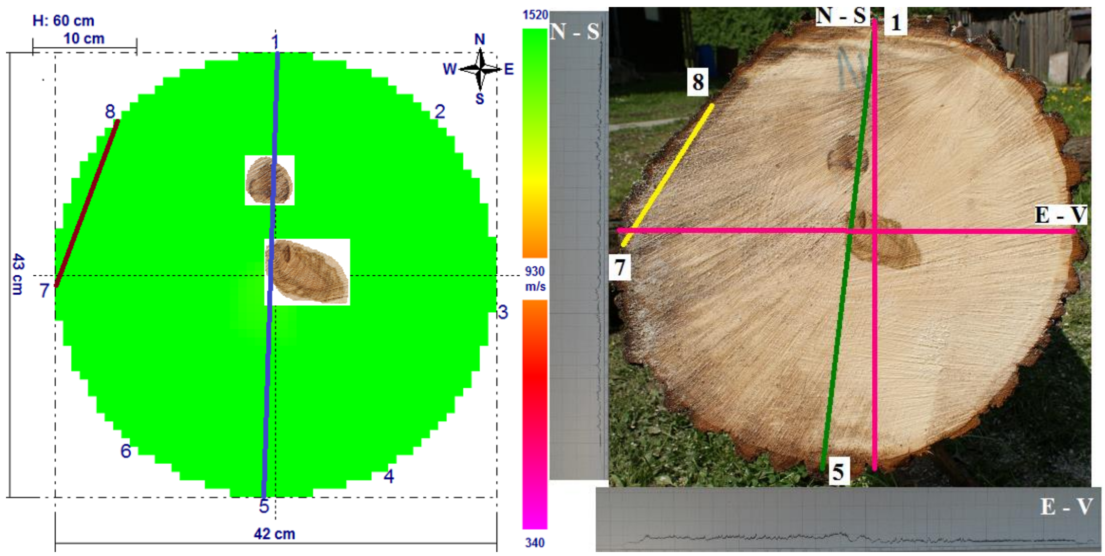


Fig. 15. Non-identification of defects on the 60 cm section at the second piece of wood

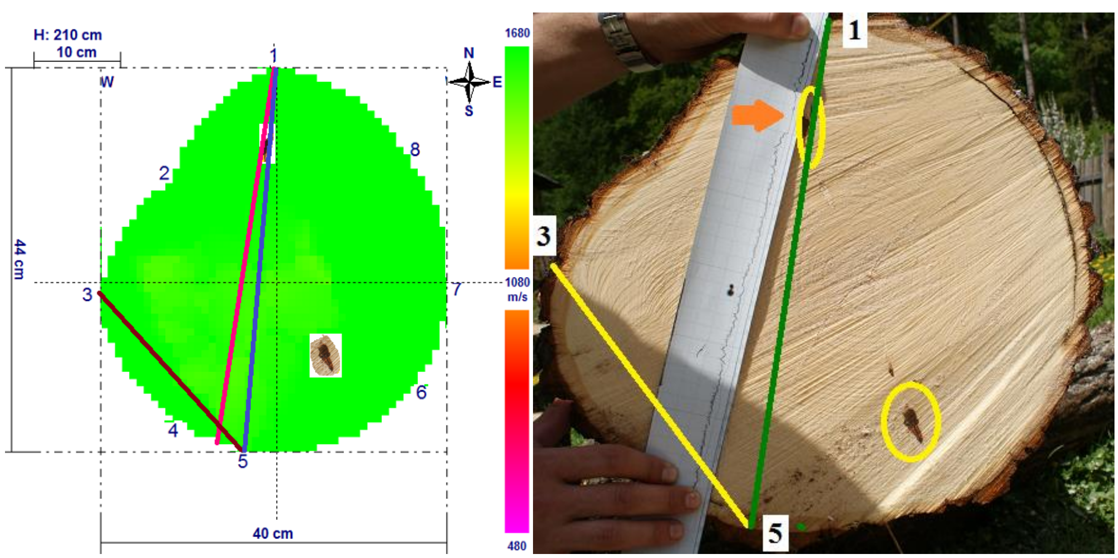


Fig. 16. Failure to identify defects on the 210 cm section at the second piece of wood

The second piece of wood drew attention, in particular, at the 10 cm section, due to the presence of the rot and a hollow, which were visible on the thick end of the piece. The measurements done by the sonic tomograph led to the establishment of an area with low speeds, but the severity of the internal defect was not established, as it appears on the newly created section (Fig. 17). Similar findings were described by Liang and Fu (2012), who mentioned that sonic tomographs can detect internal hollows, but they cannot determine their exact shape. In addition, it is noted that the device did not identify the presence of a knot near sensor 4. These findings agree with those who claimed that the average accuracy of rot samples is 90% when using the sound method (Wang *et al.* 2007; Wang *et al.* 2009).

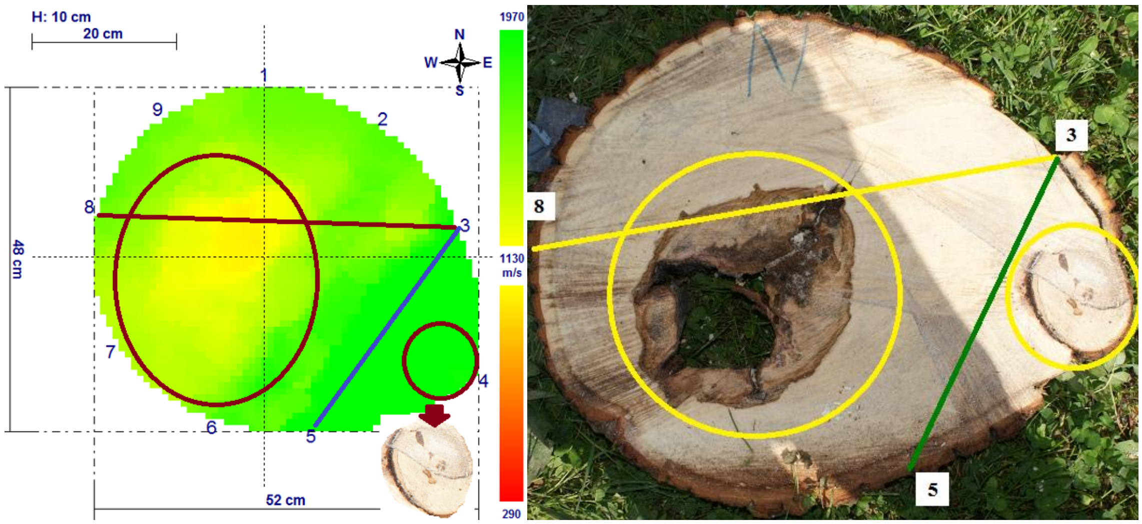


Fig. 17. Identifying a hollow and a rotten area

		1	2	3	4	5	6	7	8	9
Sensor ID		6091	6092	6093	6094	6095	6096	6097	6098	6099
6091	1		1132	1138	967	1130	1018	951	1077	889
6092	2	1102		1099	992	1421	1411	1050	1193	1163
6093	3	1026	807		1079	1475	1429	1176	964	1032
6094	4	1076	926	1223		1106	1188	1059	687	806
6095	5	1168	1426	1947	1138		1011	992	741	1066
6096	6	1047	1323	1520	1133	811		881	886	997
6097	7	942	966	1176	1012	879	881		856	993
6098	8	1093	1169	300	724	753	966	304		957
6099	9	922	1107	1105	925	993	1036	1086	1227	

Fig. 18. The minimum and maximum speeds for the section situated at 10 cm of the thick end of the second piece of wood (red color – the minimum values; blue color – the maximum speed; purple color – the speed lower than 1000 m/s)

Regarding the extreme sound speeds, for this section it was found that the minimum value was recorded on the directions of sensors 8-3 (300 m/s), respectively 8-7 (304 m/s), and the maximum value, on the direction of the sensors 5-3 (1947 m/s). A detailed analysis of the sound propagation speeds, calculated by the tomograph based on the propagation times validated by the device (Fig. 18) indicates that, in the directions traversing the defect, relatively low values of speeds were obtained, ranging from 687 m/s (between sensors 4-

8) and 993 m/s (between sensors 9-5). In addition, as the direction of propagation moved away from the defect, the values of the speed increased.

Resistance measurements completed the tomogram data, but using this method, may not give the desired results if the position of the internal defect is unknown, as checking the resistance of drilling remains a one-way assessment of wood quality (http://au.ictinternational.com/casestudies/example-arbotom-report/). However, in the present situation, the knowledge of the defect led to obtaining some valuable information, as the relative resistances to drilling became very low in the rotten area and null in the hollow (Fig. 19).

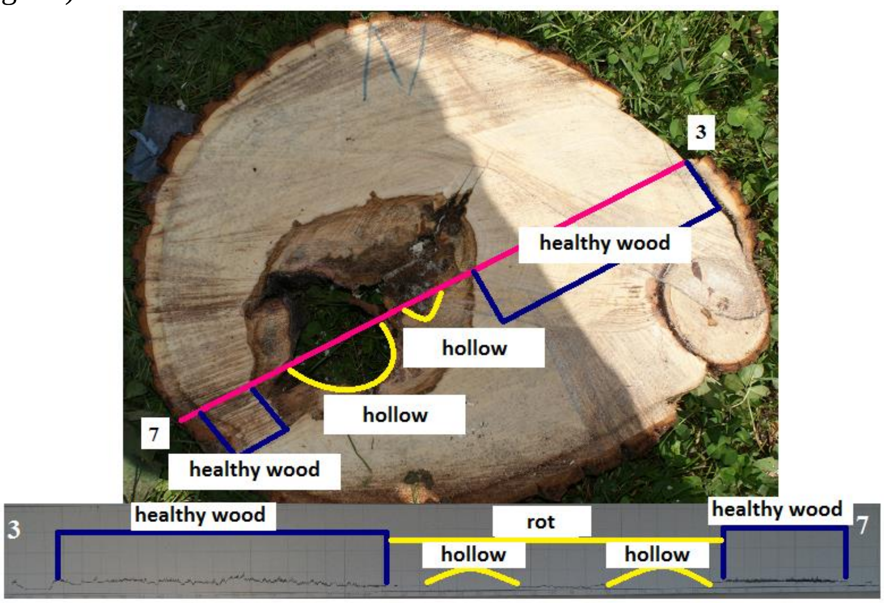


Fig. 19. The diagram of relative resistance to drilling registered between sensors 7-3

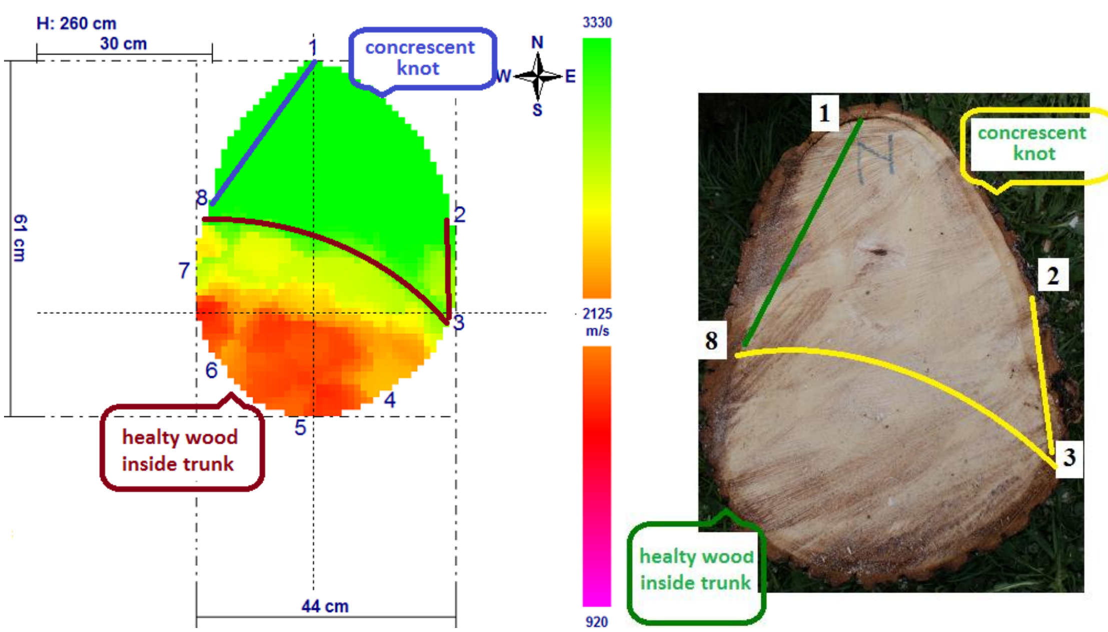


Fig. 20. Propagation of sounds through the trunk and through a healthy knot (the first piece)

The evaluation of wood quality using acoustic tomograms can lead to false diagnoses (Wang *et al.* 2009), which happened for two sections given as examples in this research. Therefore, there are two situations in which tomograms indicated by color a questionable quality of a portion of the trunk, with speeds of propagation much lower than those of the surrounding wood. Those are the cases for the 260 cm section of the first piece of wood (Fig. 20) and the 160 cm section of the third piece analyzed (Fig. 21).

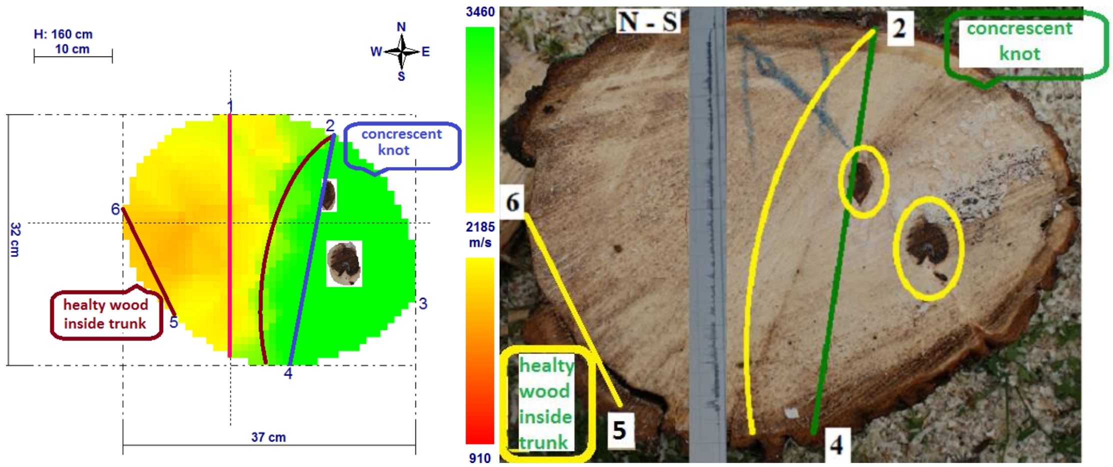


Fig. 21. Propagation of sounds through the trunk and through a healthy/living knot (the third piece)

It is imperative to check the speeds of sound propagation. From this point of view, at both levels, the registered values exceed the transfer speeds of the sound waves known for lime wood (1400 m/s, Sandoz and Lorin 1996). Unlike degraded areas, where the waves propagate at lower speeds, in the case of the two sections it was observed that the minimum speeds were 936 m/s at the first piece (value recorded between sensors 3-2) and 927 m/s on the third piece (between sensors 6-5), and the maximum recorded speeds (3294 m/s - first piece, between sensors 1-8 and 3069 m/s on the third piece, between sensors 2-4) are closer to the known speed for the transfer of sounds along the fiber (3700 m/s, Beldeanu 2008), than to the transfer speeds in the transverse plane.

The analysis of all speeds recorded by the tomograph at the analyzed levels indicates a very significant share of values exceeding 1500 m/s (63% for the first piece and 60% for the third piece). To eliminate misinterpretation of the colors illustrated by the tomogram, the color grid and the corresponding speeds for them must be analyzed. The colors that would normally illustrate degraded parts, in the case of those two tomograms, indicate speeds greater than 1500 m/s, which could not correspond, in any case, to structural defects that could affect the integrity of the wood. The differentiation by color on tomograms of the different areas is closely related to the speed of propagation of stress waves, indicating the differentiation that occurs between wood sectors which have a greater or lesser ability to transfer sound waves (Feng *et al.* 2014). It is known that the wood has the ability to receive and to transmit sound energy (Beldeanu 1999; Beldeanu 2008), this characteristic depending on a number of factors, such as humidity, density and orientation of the fibers in relation to the sound energy field (Garett 1997; Lindström *et al.* 2009; Leboucher 2014; Alves *et al.* 2015).

To clarify what is happening inside the wood, at the level of the two analyzed sections, resistograms (diagrams with the relative resistance to drill) were made. They indicated average relative resistances for lime wood, but with various oscillations, corresponding to increased relative resistances (Fig. 18). This phenomenon is explained by the fact that the unidirectional determination of the wood density, as a result of the use of the wood drilling machine, is closely related to the width of the annual rings (De Ridder *et al.* 2011; Siegert 2013). In addition, the density is influenced by the proportion of latewood (Beaulieu and Dutilleul 2019), which, unlike earlywood, has other characteristics of fibers (De Ridder *et al.* 2011; Wang and Carter 2015). Increments in density are influenced by the significant share of cells with a role of resistance, with thicker walls (Beldeanu 1999; Beldeanu 2008), and some stated that the latewood from the annual rings has a density of 1.5 … 3 times higher than earlywood (Filipovici 1964; Suciu 1975).

After extracting the probes, it was found that, in those areas, the wood was perfectly healthy, and the very high speeds and, respectively, the frequent oscillations of the relative resistances to drilling were due to the presence of green branches, so to a healthy knot (from a live branch) (Filipovici 1964; Beldeanu 1999; Beldeanu 2008). In this way, the results of the investigations are fully justified by the fact that the knots lead to structural changes of the wood in the trunk, inside which there are deformations of the fibers (Balleux 2004; Budakci and Cinar 2004). In the case of green branches, once with the formation of a new annual ring on the trunk, a similar one is formed on the branch, but much thinner (Beldeanu 1999; Beldeanu 2008). Because the sound wave, alike the drill of the wood drilling machine, must cross all annual growths, namely latewood, earlywood and narrower rings (Sandoz and Lorin 1996), the stress wave is propagating faster in hard, high-density wood from the healthy knot (Wang *et al.* 2007; Du *et al.* 2015; Wu *et al.* 2018; Proto *et al.* 2020).

CONCLUSIONS

1. Checking the transfer speeds of sound waves through wood can give appropriate results in the wood with significant structural defects.
2. Small internal defects can be omitted by sound waves that develop in the direction of the sensors, which prevents them from being evident in tomographic images.
3. The internal irregularities of wood, such as wide annual rings, are perceived as low-density, low-speed portions of sound transfer through the wood and, as a result, can lead to improper staining of tomograms.
4. The presence of the healthy knots at the level of the investigated sections can lead to a misinterpretation of the tomograms if proper attention is not paid to the transfer rates of stress waves.
5. The determination of drilling relative resistances gives very good results on wood integrity, much more accurate than tomograms, but they have the great disadvantage of referring only to the condition of the wood on the direction of the drilling and not for the whole investigated section.

ACKNOWLEDGEMENTS

The author thanks the Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, for the logistics and equipment needed for this study, and to my husband who help me in field measurements.

REFERENCES

Allison, R. B., and Wang, X. (2015). ”Nondestructive testing in the urban forest,” in: *Nondestructive evaluation of wood*, 2nd Ed., R. J. Ross (ed.), General Technical Report FPL-GTR-238. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA.

Alves, R. C., Mantilla, J. N. R., Bremer, C. F. and Carrasco, E. V. M. (2015). ”Application of acoustic tomography and ultrasonic waves to estimate stiffness constants of *Muiracatiara* Brazilian wood,” *BioResources* 10(1), 1845-1856.

Balleux, P. (2004). “Les défauts du bois,”*Silva Belgia* 523-28 (I-VI).

Bartens, J., Wiseman, P. E., and Smiley, E. T. H. (2010). “Stability of landscape trees in engineered and conventional urban soil mixes,” *Urban Forestry & Urban Greening* 9, 333-338. DOI: 10.1016/j.ufug.2010.06.005

Beaulieu, J., and Dutilleul, P. (2019). “Applications of computed tomography (CT) scanning technology in forest research: A timely update and review,” *Canadian Journal of Forest Research* 49, 1173-1188. DOI: 10.1139/cjfr-2018-0537

Beldeanu, E. (1999). *Produse Forestiere şi Studiul Lemnului, vol. I.* [*Wood products and wood study – vol. I*], Transilvania University Press, Brasov, Romania.

Beldeanu, E. (2008). *Produse forestiere* [*Wood products*], Transilvania University Press, Brasov, Romania.

Bouchet, A., and Danneau, F. G. M. (2017). “La vitesse du on dans different milieux,” *Printemps des Sciences* 17, 3p.

Brancheriau, L., Ghodrati, A., Gallet, P., Thaunay, P. and Lasaygues, P. (2012). ”Application of ultrasonic tomography to characterize the mechanical state of standing trees (*Picea abies*),” *Journal of Physics: Conference Series* 353. *10th Anglo-French Physical Conference (AFPAC 2011)*, Fréjus, France, 012007.

Brancheriau, L., Lasaygues, P., Debieu, E., and Lefebvre, J. P. (2008). “Ultrasonic tomography of green wood using a non-parametric imaging algorithm with reflected waves,” *Annals of Forest* 2008, 712-718. DOI: 10.1051/forest:200851

Bucur, V. (1986). “Les termes non diagonaux de la matrice des rigidités du bois,” *Holzforschung* 40, 315-324. DOI: 10.1515/hfsg.1986.40.5.315

Bucur, V. (2003). *Nondestructive Characterization and Imaging of Wood,* Springer Series in Wood Science, Springer-Verlag, Berlin, Germany.

Budakci, M., and Cinar, H. (2004). ”Color effects of stains on wood with knots, cracks and rots,” *Progress in Organic Coatings* 51, 1-5. DOI: 10.1016/j.porgcoat.2004.04.001

Camacho-Cervantes, M., Schondube, J. E., Castillo, A., and MacGregor-Fors, Y. (2014). ”How the people perceive urban trees? Assessing likes and dislikes in relation to the tree of a city,” *Urban Ecosystems* 17, 761-773. DOI: 10.1007/s11252-014-0343-6

Catena, A. (2004). “Thermographie et dendrodensimetre pour l’évaluation de la

stabilitédes arbres: Comparaison de résultats," *Revue Forestiére Française* 2, 164-170. DOI: 10.4267/2042/5085
David, E. C. (2011). *Cercetări privind Calitatea Arborilor pe Picior din Localităţi, Parcuri şi Aliniamente Stradale* [*Research on the quality of standing trees in localities, parks and street alignments*], Ph.D. Thesis, Transilvania University of Brasov, Romania.
De Ridder, M., Van den Bulcke, J., Vansteenkiste, D., Va Loo, D., Dierick, M., Masschaele, B., De Witte, Y., Mannes, D., Lehmann, E., Beeckman, H., Van Hoorebeke, L. and Van Acker, J. (2011). "High-resolution proxies for wood density variations in *Terminalia superba*," *Annals of Botany* 107, 293-302. DOI: 10.1093/aob/mcq224
Deflorio, G., Fink, S., and Schwarze, F. W. M. R. (2008). "Detection of incipient decay in tree stems with sonic tomography after wounding and fungal inoculation," *Wood Science and Technology* 42, 117-132. DOI: 10.1007/s00226-007-0159-0
Dinulica, F., Marcu, V., Borz, S. A., Vasilescu, M. M., and Petritan, I. C. (2016). "Wind contribution to early silver fir (*Abies alba* Mill.) compression wood development in the Romanian Carpathians," *Iforest-Biogeosciences and Forestry* 9, 927-936. DOI: 10.3832/ifor1742-008
Dinulica, F., Bucur, V., Albu, C. T., Vasilescu, M. M., Curtu, A. L., and Nicolescu, N. V. (2020). "Relevant phenotypic descriptors of the resonance Norway spruce standing trees for the acoustical quality of wood for musical instruments," *European Journal of Forest Research* 140(1), 105-125. DOI: 10.1007/s10342-020-01318-z
Divos, F., and Divos, P. (2005). "Resolution of stress wave based acoustic tomography," *14th International Symposium on Nondestructive Testing of Wood*, Eberswalde, Germania, 309-314.
Du, X., Li, J., Feng, H., and Chen, S. (2018). "Image reconstruction of internal defects in wood based on segmented propagation rays of stress waves," *Applies Sciences* 8, article ID 1778. DOI: 10.3390/app8101778
Du, X., Li, S., Li, G., Feng, H., and Chen, S. (2015). "Stress wave tomography of wood internal defects using ellipse-based spatial interpolation and velocity compensation," *BioResources* 10(3), 3948-3962.
Ellis, D. (2014). Practical use of tomography as a part of tree risk evaluation, *The 2014 Annual California Tree Failure Report Program*, USA.
Feng, H., Li, G., Fu, S., and Wang, X. (2014). "Tomographic image reconstruction using an interpolation method for tree decay detection," *BioResources* 9(2), 3248-3263.
Filipovici, J. (1964). *Studiul lemnului* [*Wood study – vol. I*] Didactical and Pedagogical Publishing House, Bucharest, Romania.
Fu, G. (ed.) (2005). *Inspection and Monitoring Techniques for Bridges and Civil Structures*, Woodhead Publishing Limited, Cambridge, UK.(https://books.google.ro/books?hl=ro&lr=&id=iFqpAgAAQBAJ&oi=fnd&pg=PP1&dq=Inspection+and+monitoring+techniques+for+bridges+and+civil+structures&ots=ob08A8blkO&sig=lzyCkrXXmL-DzofRlhpsifad35o&redir_esc=y#v=onepage&q=Inspection%20and%20monitoring%20techniques%20for%20bridges%20and%20civil%20structures&f=false), Accessed 15 May 2022.
Garrett, S. (1997). *Tree Defect Detection*,U.S. Department of Agriculture Forest Service. (https://books.google.ro/books?hl=ro&lr=&id=mdjYyvLZ8dwC&oi=fnd&pg=PA1&dq=Garrett,+S.+(,+1997).+Tree+defect+detection.&ots=T8_zUR_oCo&sig=yeW-

2HgT_QCRIcynMob8WLD2QcU&redir_esc=y#v=onepage&q&f=false), Accessed 15 May 2022.
ICT International (2022). "Example Arbotum Report," (http://au.ictinternational.com/casestudies/example-arbotom-report/), Accessed 05 October 2022.
ICT International (2022). "Detecting Fungal Decay in Palm Stems by Resistance Drilling," (http://ictinternational.com/casestudies/detecting-fungal-decay-in-palm-stems-by-resistance-drilling), Accessed 15 May 2022.
IML (2022). "IML-RESL PowerDrill®," (https://www.iml-service.com/product/iml-powerdrill/), Accessed 05 October 2022.
Karlinasari, L., Mariyanti, I. L., and Nandika, D. (2011). "Ultrasonic wave propagation characteristic of standing tree in urban area," in: *17th International Nondestructive Testing and Evaluation of Wood Symposium*, Sopron, Hungary, 1, 151-157.
Kazemi, S., Shalbafan, A., and Ebrahimi, G. (2009). "Internal decay assessment in standing beech trees using ultrasonic velocity measurement," *European Journal of Forest Research* 128(4), 345-350. DOI: 10.1007/s10342-009-0269-3
Kirkpatrick, J. B., Davison, A., and Daniels, G. D. (2012). "Resident attitudes towards trees influence the planning and removal of different types of trees in eastern Australian cities," *Landscape and Urban Planning* 107, 147-158. DOI: 10.1016/j.landurbplan.2012.05.015
Lear, G. C. (2005). *Improving the Assessment of in situ Timber Members with the Use of Nondestructive and Semi-destructive Testing Techniques*, Master's Thesis, North Carolina State University, USA.
Leboucher, B. (2014). "Fabriqueren bois massif: Anticiper les variations," *Le Bouvet* 167, 21-33.
Li, G., Wang, X., Feng, H., Wiedenbeck, J., and Ross, R. J. (2014). "Analysis of wave velocity patterns in black cherry trees and its effect on internal decay detection,"*Computers and Electronics in Agriculture* 104, 32-39. DOI: 10.1016/j.compag.2014.03.008
Liang, S., Fu, F., Lin, L., and Hu, N. (2010). "Various factors and propagation trends of stress waves in cross sections of Euphrates poplar," *Forest Products Journal* 60(5), 440-446. DOI: 10.13073/0015-7473-60.5.440
Liang, S., and Fu, F. (2012). "Relationship analysis between tomograms and hardness maps in determining internal defects in Euphrates poplar," *Wood Research* 57(2), 221-230.
Lin, C. J., Kao, Y. C., Lin, T. T., Tsai, M. J., Wang, S. Y., Lin, L. D., Wang, Y. N., and Chan, M. H. (2008)."Application of an ultrasonic tomographic technique for detecting defects in standing trees," *International Biodeterioration and Biodegradation* 62(4), 434-441. DOI: 10.1016/j.ibiod.2007.09.007
Lin, C. J., Chang, T. T., Juan, M. Y., and Lin, T. T. (2011). "Detecting deterioration in royal palm (*Roystonea regia*) using ultrasonic tomographic and resistance microdrilling techniques," *Journal of Tropical Forest Science* 23, 260-270.
Lin, W., and Wu, J. (2013). "Study on application of stress wave for nondestructive test of wood defect," *Applied Mechanics and Materials* 401-403, 1119-1123. DOI: 10.4028/www.scientific.net/AMM.401-403.1119
Lindström, H., Reale, M., and Grekin, M. (2009). "Using non-destructive testing to assess modulus of elasticity of *Pinus sylvestris* trees,"*Scandinavian Journal of Forest Research* 24(3), 247-257.DOI: 10.1080/02827580902758869

Lunguleasa, A. (2004). *Anatomia şi Mecanica Lemnului* [*Wood anatomy and mechanics*],Transilvania University Publishing House, Brasov, Romania.

Malinovski, R. A., Nutto, L., Schwegler Wiese, W., and Brunsmeier, M. (2016). "Non-destructive analysis of the root system and tree growth parameters," *Revista Árvore* 40(2), 289-295. DOI: 10.1590/0100-67622016000200011

Martinis, R., Socco, L., Sambuelli, L., Nicolotii, G., Schmitt, O., and Bucur, V. (2004). "Tomographie ultrasonore pour les arbres sur pied," *Annals of Forest Science, Springer Nature* 61(2), 157-162.

Moravčík, L., Vincúr, R., and Rózová, Z. (2021). "Analysis of the static behavior of a singel tree on a finite element method," *Plants* 10, article 1284. DOI: 10.3390/plants10071284

Mu, H., Qi, D., Zhang, M., and Zhang, P. (2010). "Study of wood defects detection based on image processing," *Seventh International Conference on Fuzzy Systems and Knowledge Discovery (FSKD 2010)*, 607-611.

Musat, E.C., Ciubotaru, A., and Ciobanu, V. D. (2014). "The external defects and the particularities of the trees crowns located into the green areas of Brasov," *Conference Proceedings of the International Multidisciplinary Scientific Geoconferences (SGEM 2014), 14th GeoConference on Water Resources. Forest, Marine and Oceanic Ecosystems*, Albena, Bulgary, 461-468.

Musat, E. C., Derczeni, R. A., Barti, M. E., and Dumitru-Dobre, C. (2020). "Analysis of sound velocity through the wood of spruce trees located into a burned area," *Forestry Bulletin* T.24(4), 98-109.

Nicolotti, G., Socco, L. V., Martinis, R., Godio, A., and Sambuelli, L. (2003). "Application and comparison of three tomographic techniques for detection of decay in trees," *Journal of Arboriculture* 29(2), 66-78. DOI: 10.48044/jauf.2003.009

Nimară, D., Voiculescu, P., and Pavelescu, I. M. (1964). *Cartea Sortatorului de Produse Lemnoase de Pădure* [*Forest Wood Product Sorter's Book*], Agro-Forestry Publishing House, Bucharest, Romania.

Ostrovsky, R., Kobza, M., and Gazo, J. (2017). "Extensively damaged trees tested with acoustic tomography considering tree stability in urban greenery," *Trees* 31, 1015-1023. DOI: 10.1007/s00468-017-1526-6

Parascan, D., and Danciu, M. (2001). *Fiziologia Plantelor Lemnoase cu Fundamente de Fiziologie Vegetală Generală* [*Physiology of woody plants with fundamentals of general plant physiology*], For Life, Brasov, Romania.

Proto, A. R., Cataldo, M. F., Costa, C., Papandrea, S. F., and Zimbalatti, G. (2020). "A tomographic approach to assessing the possibility of ring shake presence in standing chestnut trees," *European Journal of Wood and Wood Products* 78, 1137-1148. DOI: 10.1007/s00107-020-01591-0

Qu, H., Chen, M., Hu, Y., and Lyu, J. (2020). "Effect of trees knot defects on wood quality: A review," *IOP Conference Series: Materials Science and Engineering*, 738(1), in: *2019 International Conference on Energy, Chemical and Material Science* (ECMS 2019), Malaysia, 012027. DOI: 10.1088/1757-899X/738/1/012027

Rinn, F. (1988). *A New Method for Measuring Tree-ring Density Parameters*, Physics Diploma Thesis, Institute for Environmental Physics, Heidelberg University, Germany.

Rinn, F. (1994). "Resistographie visualization of tree-ring density variations," in: *International Conference on Tree Rings, Environment and Humanity. Relationships and Processes*," Tucson Arizona, USA.

Rinn, F. (2014). "Central basics of sonic tree tomography," (https://ictinternational.com/casestudies/central-basics-of-sonic-tree-tomography/), Accessed 04 October 2022.

Rinntech (2022). "Products and services for tree and wood analysis," (http://rinntech.de), Accessed 15 May 2022.

Rohanová, A. (2009). "Characteristics of spruce timber quality determined by ultrasonic and bending method," *Annals of Warsaw University of Life Sciences – SGGW, Forestry and Wood Technology* 60, 234-238.

Ross, R., Brashaw, B., and Pellerin, R. (1998). "Nondestructive evaluation of wood," *Forest Production Journal* 48(1), 14-19.

Ross, R. J., and De Groot, R. C. (1998). "Scanning technique for identifying biologically degraded areas in wood members," *Experimental Techniques* 22(3), 32-33. DOI: 10.1111/j.1747-1567.1998.tb01282.x

Roughton, J. E. (1982). "Non-invasive measurements. *Journal of Physics E: Scientific Instruments* 15(2), 12-57. DOI: doi.org/10.1088/0022-3735/15/12/002

Saebø, A., Borzan, Ž., Ducatillion, C., Hatzisrtathis, A., Lagerström, T., Supuka, J., García-Valdecantos, J. L., Rego, F., and van Slycker, J. (2005). "The selection of plant materials for street trees, park trees and urban woodland," in: *Urban Forests and Trees, C.* Konijnendijk, K. Kilsson, T. Randrup, T. Schipperijn (eds.), Springer, Berlin, Germany.

Sandak, J., Sandak, A., Zitek, A., Hintestoisser, B., and Picchi, G. (2020). "Development of low-cost portable spectrometers for detection of wood defects," *Sensors* 20(2), article 545, 19 p. DOI: 10.3390/s20020545

Sandoz, J. L., and Lorin, P. (1996). "Tares internes de bois sur pied: détection par ultrasons," *Revue Forestiére Français - Technique et Forêt* XLVIII(3), 231-240.

Seifert, T., Nickel, M., and Pretzsch, H. (2010). "Analyzing the long-term effects of artificial pruning of wild cherry by computer tomography," *Trees* 24, 797-808. DOI: 10.1007/s00468-010-0450-9

Siegert, B. (2013). "Comparative analysis of tools and methods for the evaluation of tree stability," *Results of a field test in Germany. Arborist News*, 26-31.

Suciu, P. (1975). *Lemnul: Structură, Proprietăţi, Tehnologie* [*Wood: structure, properties and technology*], Ceres, Bucharest, Romania.

Tarasiuk, S. T., Jednoralski. G., and Krajewski, K. (2007). "Quality assessment of old-growth Scots pine stands in Poland," *COST E53 Conference – Quality Control for Improving Competitiveness of Wood Industries*, Warsaw, Poland, 153-160.

Tomikawa, Y., Iwase, Y., Arita, K., and Yamada, H. (1986). "Nondestructive inspection of a wooden pole using ultrasonic computed tomography," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*. 33, 354-358. DOI: 10.1109/T-UFFC.1986.26842

Troxel, B., Piana, M., Ashton, M. S., and Murphy-Dunning, C. (2013). "Relationships between bole and crown size for young urban trees in the northeastern USA," *Urban Forestry and Urban Greening* 12, 144-153. DOI: 10.1016/j.ufug.2013.02.006

vanWassenaer, P. (2010). "Minimally-invasive tree risk assessment: A Canadian perspective,"*44th National Amenity Arboriculture Conference,* Manchester, Anglia.

van Wassenaer, P., and Richardson, M. (2009). "A review of tree risk assessment using minimally invasive technologies and two case studies," *Arboricultural Journal* 32(4), 275-292. DOI: 10.1080/03071375.2009.9747583

Wang, L., Xu, H., Zhou, C., Li, L., and Yang, X. (2007). "Effect of sensor quantity on measurement accuracy of log inner defects by using stress wave," *Journal of Forestry Research* 18(3), 221-225. DOI: 10.1007/s11676-007-0045-5

Wang, X., Wiedenbeck, J., and Liang, S. (2009). "Acoustic tomography for decay detection in black cherry trees," *Wood and Fiber Science* 41(2), 127-137.

Wang, X., and Allison, R. B. (2008). "Decay detection in red oak trees using a combination of visual inspection, acoustic testing, and resistance microdrilling," *Arboriculture and Urban Forestry*34(1), 1-4. DOI: 10.48044/jauf.2008.001

Wang, X. (2013). "Acoustic measurements on trees and logs: A review and analysis," *Wood Science and Technology* 47(5), 965-975. DOI: 10.1007/s00226-013-0552-9

Wang, X., and Carter, P. (2015). "Chapter 8: Acoustic assessment of wood quality in trees and logs," in: *Nondestructive Evaluation of Wood: Second Edition*, R.J. Ross (ed.), General Technical Report FPL-GTR-238, USA.

Wu, X. G., Li, Z., and Jiao, W. X. (2018). "Reliability of acoustic tomography and ground-penetrating radar for tree decay detection," *Applications in Plant Sciences* 6(10), article 187. DOI: 10.1002/aps3.1187

Wunder, J., Manusch, C., Queloz, V., Brang, P., Ringwald, V., and Bugmann, H. (2013). "Does increment coring enhance tree decay? New insights from tomograph assessments," *Canadian Journal of Forest Research* 43, 711-718. DOI: 10.1139/cjfr-2012-0450

Article submitted: October 8, 2022; Peer review completed: December 31, 2022; Revised version received and accepted: January 9, 2023; Published: January 18, 2023.
DOI:10.15376/biores.18.1.1757-1779