How Well Can Sound Tomograms Characterize Inner-Trunk Defects in Beech Trees from a Burned Plot?

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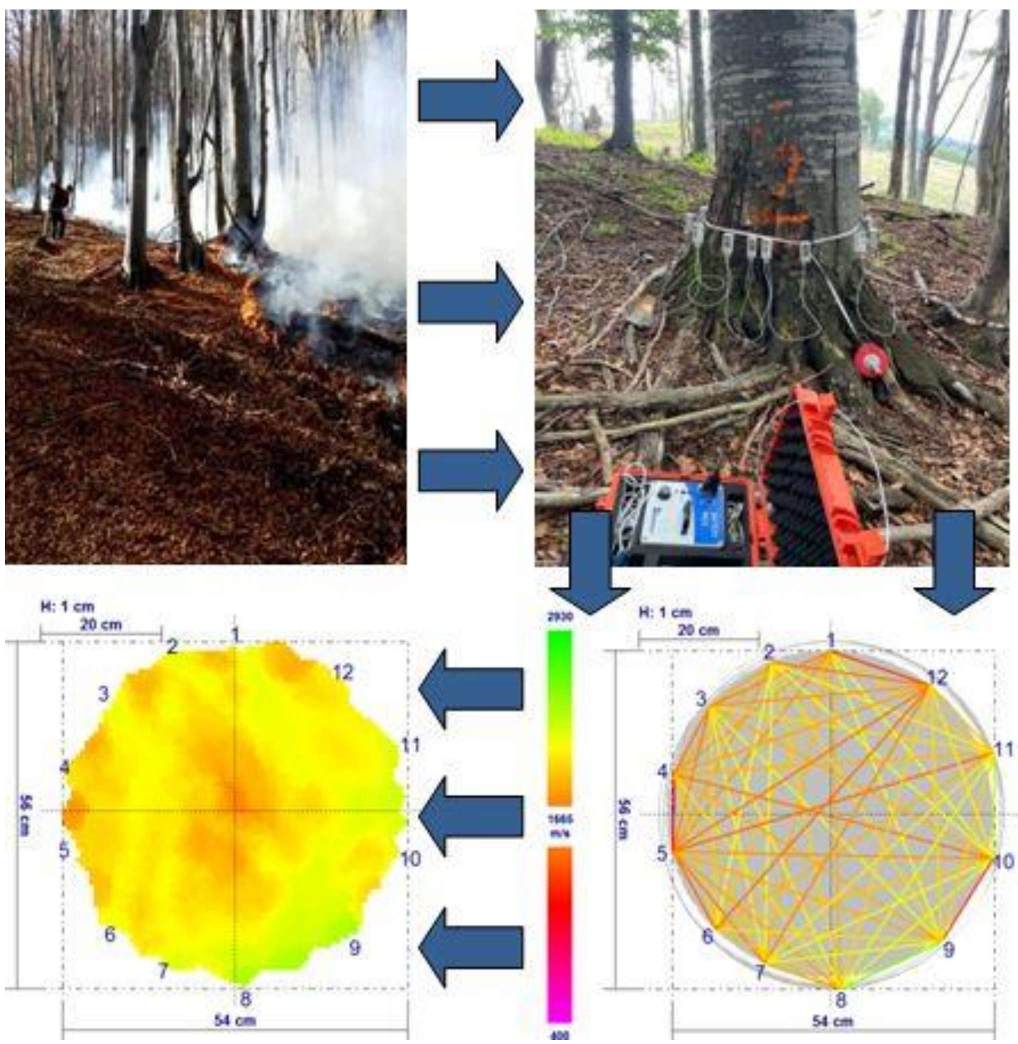
GRAPHICAL ABSTRACT



How Well Can Sound Tomograms Characterize Inner-Trunk Defects in Beech Trees from a Burned Plot?

Elena C. Musat *

In recent years, forest fires have become increasingly common, but also more damaging phenomena. These aspects are reflected in significant economic losses that affect the quality and quantity of wood volumes that can be used for industrial processing. For this reason, knowing the quality of the wood is important, especially in fire-affected trees. Because visual analyses cannot always reflect the quality of the wood inside the trunk, the present research aimed to evaluate the extent to which modern techniques based on the transfer of sounds can identify internal wood defects. In this sense, 42 tomograms made from beech trees affected by a litter fire were compared with the relative resistances of the wood to drilling and with the real condition of the wood inside the trunk, as made visible through the growth cores taken with a Pressler drill. From the cumulative interpretation of the results, it was found that the trees affected by the fire have serious defects, which lead to the downgrading of the wood and are not reproduced by the tomograph to their true extent. Conversely, sound transfer speeds through wood are influenced by the presence of beech red heartwood, which leads to an increase in sound transfer speeds through wood, and that can alter the accuracy of the tomogram.

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Keywords: Sound speeds in wood; Tomogram;Resistogram; Relative resistances to drilling; Beech; Forest fires; Romania

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INTRODUCTION

Globally, forest cover has seen fluctuations that have become increasingly visible and worrisome in recent decades (Palaghianu 2007; Meddour-Sahar *et al.* 2013), even if forests represent the most important renewable resource on the planet (Ene *et al.* 2013; Moskalik and Gendek 2019), having an essential role in the carbon cycle in nature (Palaghianu 2007; Moradi *et al.* 2022). One of the main factors that has led to the destruction of forests is man, who cut down forests to obtain areas suitable for agricultural crops (Palaghianu 2007; Meddour-Sahar *et al.* 2013). This has been practiced worldwide, but the largest changes in land use category recently have been recorded in the tropics (Palaghianu 2007; Armenteras *et al.* 2017).

Forest fires also have a devastating impact on forests (Meddour-Sahar *et al.* 2013; Foldi and Kuti 2016; Calviño-Cancela *et al.* 2017). Catastrophic fires affect the entire ecosystem (Palaghianu 2007; Guêné-Nanchen *et al.* 2021), starting from the soils (Brandstock 2008; Page-Dumroese *et al.* 2019), plants and animals, affecting water resources, as well as increasing greenhouse gases (Harrison *et al.* 2009). In addition, regardless of the type of fire and their aggressiveness, the role of the forest as a whole is endangered (Armenteras *et al.* 2017), and there is harm to the anti-erosion protection functions (Brandstock 2008) and the capabilities for storing rainwater and air purification (Földi and Kuti 2016; Hossain *et al.* 2020). It is known that forests represent the "lungs" of the planet through a net conversion of carbon dioxide to oxygen.

Forest fires represent calamities that affect the entire planet regardless of continent, such as in America (Gillet *et al.* 2004; Guêné-Nanchen*et al.* 2021), Asia (Harrison *et al.* 2009; Çoban and Eker 2010; Meddour-Sahar *et al.* 2013; Tian *et al.* 2013), Australia (Acuna *et al.* 2017), Europe (Dimitrakopoulos and Panov 2001; Pereira Domingues Martinio 2019)–or climate zone–boreal forests (Hély *et al.* 2000; Tian *et al.* 2013; Guêné-Nanchen *et al.* 2021), temperate forests (Adam 2007; Çoban and Eker 2010; Sivrikaya *et al.* 2015; Burlui and Burlui 2018), or tropical forests (Harrison *et al.* 2009; Meddour-Sahar *et al.* 2013; Armenteras *et al.* 2017). The devastating effects of fires are not limited to their local impact on the forest, with all its components (Sivrikaya *et al.* 2015), but also on people (Harrison *et al.* 2009; Calviño-Cancela *et al.* 2017), reaching losses of millions of Euros (Földi and Kuti 2016), and damage to millions of hectares of forest annually (Barreal *et al.* 2012). Even if forest fires have affected humanity and the environment since ancient times, they only occur in situations where three fire initiation conditions are met simultaneously, defining the "fire triangle" (Omi 2005; Lieberman 2008; Burlui and Burlui 2018), without which a fire could not occur, respectively, the ignition source, the combustible (the gas that ensures combustion), and the fuel (the combustible material).

The growing demand for wood at an international level includes industrial uses (Proto *et al.* 2020; Qu *et al.* 2020; Staže *et al.* 2021; Harvey and Visser 2022; Papandrea *et al.* 2022), as well as for obtaining energy benefits (Tenchea *et al.* 2019; Proto *et al.* 2020). The assessment of the impact of forest fires on the wood in the forests, especially on the remaining trees in the burned areas, plays an extremely important role, in particular for limiting or reducing the economic losses due to the depreciation of the wood (Rodríguez y Silva *et al.* 2012; Musat *et al.* 2020). In addition, knowing the quality of the wood inside the trunk can help establish measures to limit economic losses (Sandoz and Lorin 1996; Burlui and Burlui 2018), for example, using these trees as quickly as possible (Rodríguez y Silva *et al.* 2012). Such knowledge is needed even if this means that the trees are harvested before the age of exploitability (Rodríguez y Silva *et al.* 2012), at which it is considered that the best qualities and volumes of wood would ordinarily be obtained.This aspect is important especially because trees affected by fires, where the trunk or base show visible signs of burning (scorched or burned bark, fallen from the trunk, scorched or charred wood (Lawes *et al.* 2011; Odhiambo *et al.* 2014)), will vegetate in poor conditions (Musat 2017), but they will be weaker and, at the same time, more sensitive to the attack of external pathogens (Wuerther 2006; Musat *et al.* 2020). As a result of these attacks, the trunk and the base of the trunk can be affected by rot, which can develop much faster, especially along the trunk, leading to an increase in the volume of degraded wood (Feng *et al.* 2014; Sandak *et al.* 2020; Cristini *et al.* 2022; Harvey and Visser 2022).

The assessment of tree vitality and wood quality has been a topic of interest in numerous studies over time (Sandoz and Lorin 1996; Martinis *et al.* 2004; Punches 2004; Feng *et al.* 2014; Alves *et al.* 2015; Du *et al.* 2015; Espinosa *et al.* 2017; Wu *et al.* 2018; Cristini *et al.* 2022; Papandrea *et al.* 2022), and it continues to be important today.Thus, some studies evaluate the vitality of trees in various vegetation conditions, starting from visual assessments of the whole tree, with an emphasis on the crown, appearance, and quality of foliage (Ciubotaru and David 2011; David and Ciubotaru 2011; David and

Enache 2011b). Studies have usually analyzed visible defects (David and Enache 2011a; Musat *et al.* 2014; Staže *et al.* 2021) or those hidden inside the trunk (Martinis *et al.* 2004; Wang *et al.* 2007; Deflorio *et al.* 2008; Du *et al.* 2015; Proto *et al.* 2020), and studies have used destructive (growth cores, cross-cutting, splitting), semi-destructive (resistograph), or non-destructive (sound waves, X-rays, *etc.*) methods to assess the quality of the wood inside the trunk (Sandoz and Lorin 1996; Martini *et al.* 2004; Wang *et al.* 2007; Deflorio *et al.* 2008; Feng *et al.* 2014; Alves *et al.* 2015; Du *et al.* 2015; Espinosa *et al.* 2017; Musat 2017; Proto *et al.* 2020; Cristini *et al.* 2022; Papandrea *et al.* 2022; Musat 2023).

Due to the strong impact of fire on wood and the need to know more precisely the implications on quality, the purpose of the present research was to evaluate the degree to which the analysis of the transfer speeds of sounds through the wood can be used to characterize the possible defects inside the trunk, as affected by a litter fire. To achieve the proposed goal, the sound tomograph will be used with the idea of obtaining information about the transfer speeds of sounds through wood. In addition, further investigations with the resistograph and the Pressler drill were carried out to provide more precise details regarding the quality of the wood.

MATERIALS AND METHODS

To conduct field investigations, a plot under the administration of the Runcu Forest District within the Gorj County Forestry Administration (Romania), a forest privately owned by the Plaiului Vălari Municipality, was chosen. This management unit was affected by a litter fire in 2017, which took 5 days to extinguish (Fig. 1). The fire that affected the plot came from an area bordering the forest, where the owner, wanting to clear the land of dry vegetation, set it on fire and the fire got out of control. From a geomorphologic point of view, the surface of management unit number 149 is characterized by an undulating configuration of the slopes, with a predominantly north-west exposure, with slopes varying between 24 and 30°. The 34.7 ha area of the unit has a large altitudinal variation, between 700 and 1100 m. In the study area, the trees affected by fire were 93-year-old beech trees.

Fig. 1. The extinguish fight against the litter fire that occurred in 2017 in management unit number 149

As part of the determinations, 21 beech trees affected by the fire were investigated, including some that showed clear signs of scorching or burning on the trunk (Figs. 2 through 4). For each individual tree, two levels were marked with forest spray to perform the determinations, respectively at 50 and 100 cm above the ground, considered upstream from the tree, resulting in 42 analyzed tomograms. The investigations in the field first assumed the analysis of sound transfer speeds through wood, in which the ArbotomRinntech v.2 sound tomograph was used (Fig. 5), using the same working methodology as in the case of previous Musat works (2017 and 2023), respectively, and Musat *et al.* (2020).

Fig. 2. Trunk affected by fire and rot

Fig. 3. Wound produced by fire

Fig. 4. Rut at the base of the trunk developed after the fire

Fig. 5. The ArbotomRinntech tomograph and the sensors connection

An aspect that should be mentioned is that each emitting sensor had received 7 blows with the hammer provided with the device, the number being chosen in relation to the recommendations in the specialized literature (Divos and Divos 2005; Tarasiuk *et al.* 2007; Wang *et al.* 2007; Rinn 2014) and the ambient noise. In addition, before saving the measurements, sound transmission errors through the wood were checked to be less than 10% (Tarasiuk *et al.* 2007). Finally, the tomogram reconstructed by the tomograph based on the sound transmission speeds through the wood was briefly analyzed, which made it possible to obtain the points where the investigations could be carried out further with the IML RESI F500-S resistograph, equipped with a 50 cm long drill and 3 mm width of the cutting edge of the points where the growth cores will be extracted with the Pressler drill. The cores extracted were analyzed with the microscope to see where there was any modification of the wood, in the sense of any difference along the core and what defects could be identified. The information was used in the interpretation of the data. Changes were made apparent on the resistograms by marking delimitation lines between the different zones.

Thus, both the analyses with the resistograph (Fig. 6), as well as the sampling of growth cores (Figs. 7 and 8) were made on the direction of the sensors that indicated the greatest irregularities inside the trunk.

Fig. 6. The investigations made by the IML F-500 RESI resistograph

Fig. 7. The growth core extraction using the Pressler drill

Fig. 8. The extracted growth core

Of all the 21 investigated beech trees, only six are presented in the article.The detailed results and the rest of the tomograms are inserted as supplementary material (Appendix 1) at the end of the paper. The choosing of these six trees considers the diverse situations encountered in the field and in the data interpretation, allowing every case to be presented and commented on.

RESULTS

In the forest area, 21 beech trees (*Fagus sylvatica* L.) were investigated, whose diameters varied between 31 and 70 cm for the 50 cm level, between 28 and 61 cm for the 100 cm level; the diameter values were extracted from the program software, based on entering the position of the sensors on the circumference of the trunk. In the following, the most relevant results for the investigated trees are presented.

Upon visual inspection of beech tree number3 (Fig. 9), it was noted that the fire particularly affected almost half of the circumference of the trunk, between north and south, and was at a considerable height. There was also the presence of fruiting bodies of some fungi, also in the northern direction. In the southeast area, the trunk no longer had bark, and the presence of dead wood was noted. This could be justified by the fact that the fire not only affected the bark of the tree, but it led to the death of the cambial cells (Beldeanu 2001 and 2008).

Fig. 9. The aspect of the beech tree number 3 at the visual assessment

Based on a first analysis of the results offered by the tomograph, for the level of 50 cm above the ground, it could be considered that the entire section was destroyed or had serious irregularities that led to yellow-orange coloring of both the connection lines between the sensors (Fig. 10a), as well as of the tomogram (Fig. 10c). Conversely, when the images illustrated by the tomograph were compared with the speeds scale, these colors corresponded to values greater than 1500 m/s, which indicates healthy wood or with few signs of decay.

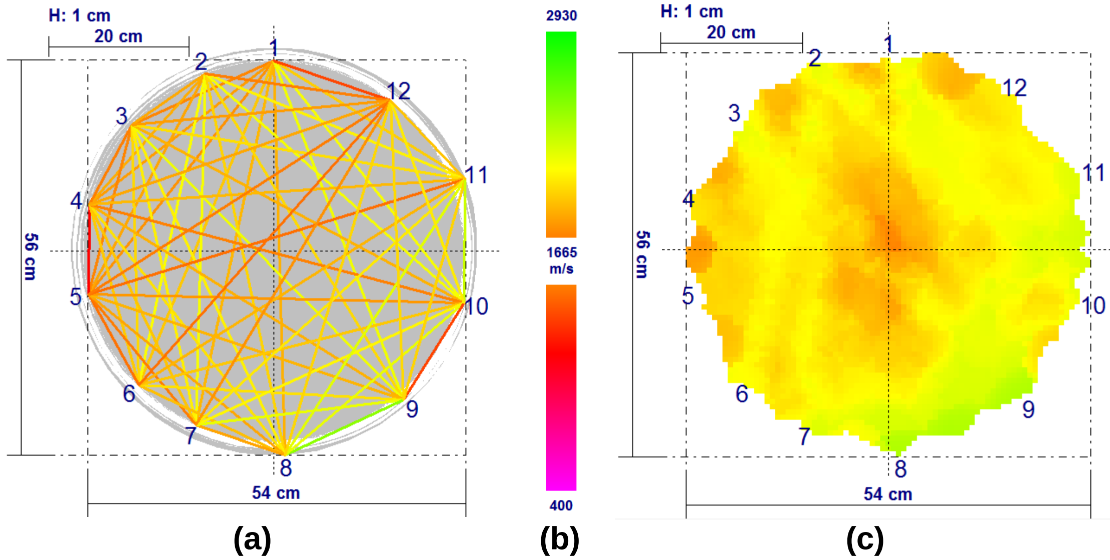


Fig. 10. The transmission of sound waves to the beech tree number 3, at the level of 50 cm: a) the links between the sensors ;b) the speeds scale; and c) the tomogram

At the level of 100 cm above the ground, things appeared normal, in the sense that both the speeds network between the sensors (Fig. 11a), as well as the tomogram (Fig. 11c) presents, with few exceptions (S_{1-2} = 854 m/s, S_{2-1} = 807 m/s, S_{3-2} = 948 m/s, S_{4-5} = 982 m/s, andS_{7-6} = 980 m/s), speeds of sound transfer over 1000 m/s, predominating those of 1400to1500 m/s.

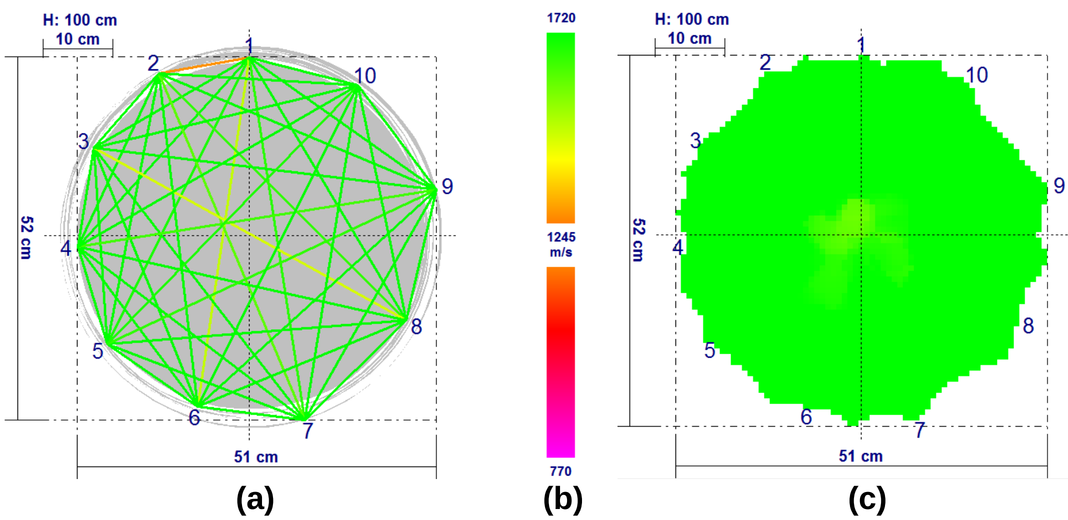


Fig. 11. The transmission of sound waves to the beech tree number 3, at the level of 100 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

Regarding the resistogram made on the direction of sensor S_1 from the level of 100 cm above the ground (Fig. 12), this indicates low relative resistances of the wood to drilling in the first 7 cm, with numerous variations, but of small amplitude, signifying degraded wood in which the structure was to some extent destroyed, an aspect that can also be identified on the growth core (Fig. 12). After the first 7 cm, the relative resistances to drilling began to increase. Larger oscillations and differences in the annual rings were apparent, and the growth core indicated healthy wood. Towards the center of the trunk, very large oscillations occurred in terms of the relative resistances of the wood to drilling, especially within the annual rings. Similar results were identified in other research (Câmpu 2010; Câmpu and Dumitrache 2015), indicating that they were due to the presence of the red heartwood of the beech, contributing to a densification of the wood, which increases its resistance (Beldeanu 2001, 2008; Câmpu 2010).

It is worth mentioning that the sensor S_1 was placed in a portion with decayed wood and dead wood, and maybe for this reason the values of relative resistances to drilling were so low in the first 7 cm of the growth core.

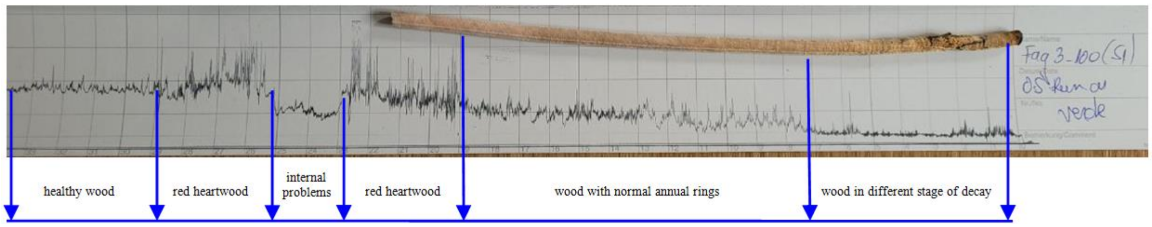
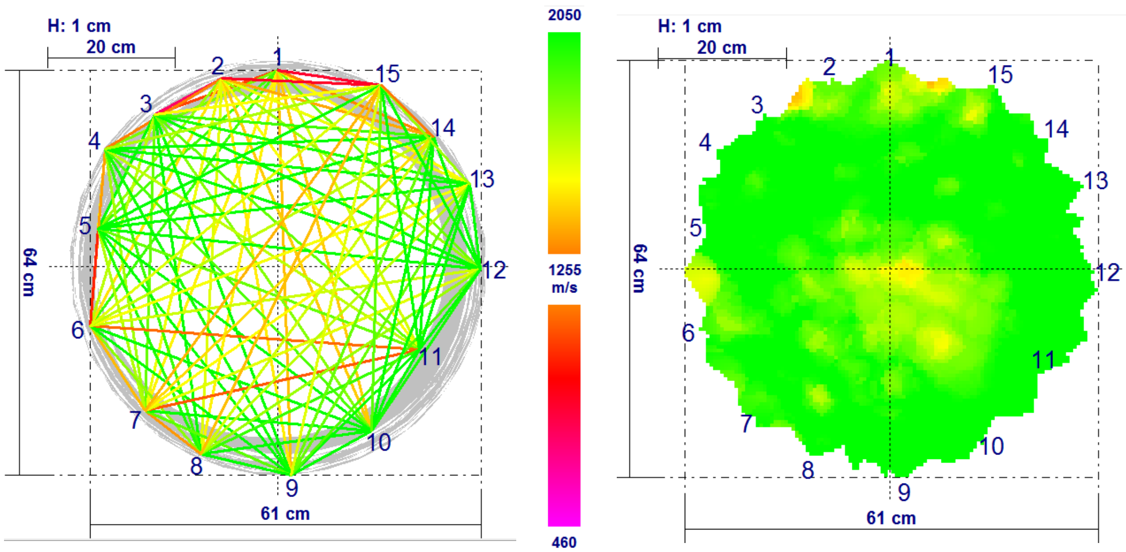


Fig. 12. The resistogram made and the growth core extracted from the beech tree number 3, from the direction of the S_1 sensor at the 100 cm level

Upon visual analysis of tree 4, it was found that it showed great signs of degradation, the fire affecting both the superficial roots and the trunk. All this led over time to a worsening of the impact of the fire on the tree and the wood, at various heights on the trunk, fruiting bodies of some xylophages fungi could be observed (Fig. 13). In addition, it is notable that the fire affected the roots and the trunk of the tree all around, the respective areas being either without bark, or with dry and cracked bark (Fig. 13).

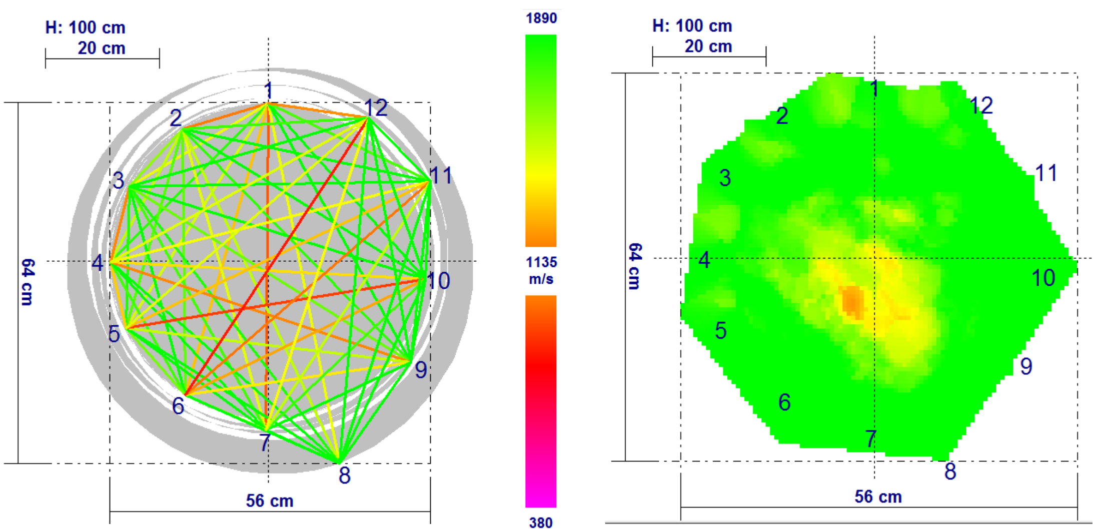
Fig. 13. The aspect of the beech tree number 4 at the visual assessment

Based on the investigations at the level of 50 cm above the ground, it was found that both the links between the sensors (Fig. 14a), as well as the tomogram (Fig. 14c) indicated some areas where sounds propagated at low speeds, especially in the case of close sensors, where values of less than 1000 m/s were also encountered. It was also observed that the tomogram made at 50 cm indicated in the center of the trunk an area where the sounds transfer speeds through the wood were lower (Fig. 14c). Such an area at the level of 100 cm became more obvious and more vividly colored, even in shades of orange (Fig. 15c).



(a) (b) (c)

Fig. 14. The transmission of sound waves to the beech tree number 4, at the level of 50 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram



(a) (b) (c)

Fig. 15. The transmission of sound waves to the beech tree number 4, at the level of 100 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

To better understand what is happening inside the trunk, at the level of 100 cm above the ground, in the direction of the sensor S_6, a resistogram was performed and a growth sample was taken (Fig. 16). From the analysis of the resistogram, inside the trunk, towards its center, there was an area where the relative resistances of the wood to drilling decreased considerably, tending towards 0. The growth core indicated, in the first 12 to 13 cm, intensely degraded wood, with very low relative resistances to drilling and almost no resistance oscillations.

At the beech tree no. 4 the resistogram and the growth core illustrate the same situation as in the case of tree no. 3, because the relative resistances from the first 12 cm were very low. Also, it is worth mentioning that the tree was dry and the sensor S_6 was placed in a portion with dead wood.

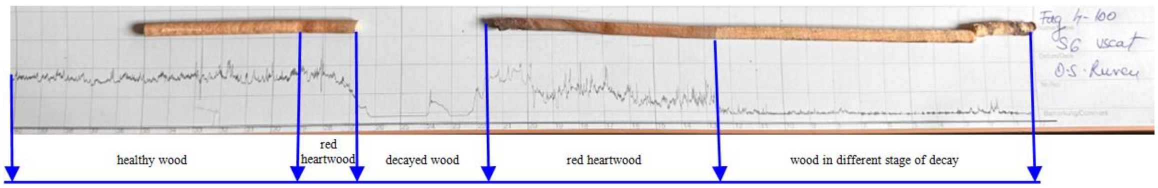


Fig. 16. The resistogram made and the growth core extracted from the beech tree number 4, from the direction of the S_6 sensor at the 100 cm level

It was also found that after this portion, the red heartwood can be identified in the core. Its presence is also indicated by the resistogram, by increasing the relative resistances to drilling, as well as by the appearance of big variations in the resistances of the wood. In addition, the red heartwood zone had a darker area towards the inside of the trunk, after which the growth core was not sampled aswoody material for several centimeters, then following the continuation of the core, on which it was observed that the wood did not appear decayed. This condition was also observed in the field at the time of core extraction, because the operator had great difficulty in extracting the growth core and the Pressler drill from the tree trunk due to the hollow inside.

Fig. 17. The aspect of the beech tree number 7 at the visual assessment

Comparing the information displayed by the resistogram and the growth core (Fig. 16) with the colors of the connecting lines between the sensors (Fig. 15a), it was observed that the sound speeds from and to the sensor S_6 did not exceed 1000 m/s (S_{6-10} = 945 m/s, S_{6-11} = 988 m/s, S_{6-12} = 899 m/s, S_{10-6} = 945 m/s, S_{11-6} = 944 m/s, S_{12-6} = 918 m/s, and S_{9-6} = 996 m/s). The visual evaluation of the beech tree no. 7 did not show any external defect, even if the tree was located in the burned area (Fig. 17). The investigation made with the sonic tomograph ArbotomRinntech at the 50 (Fig. 18) and, respectively, at 100 cm above ground (Fig. 19), did not indicate any defect or irregularities inside the trunk because the sound speeds were predominantly higher than 1500 m/s, which indicated healthy wood.

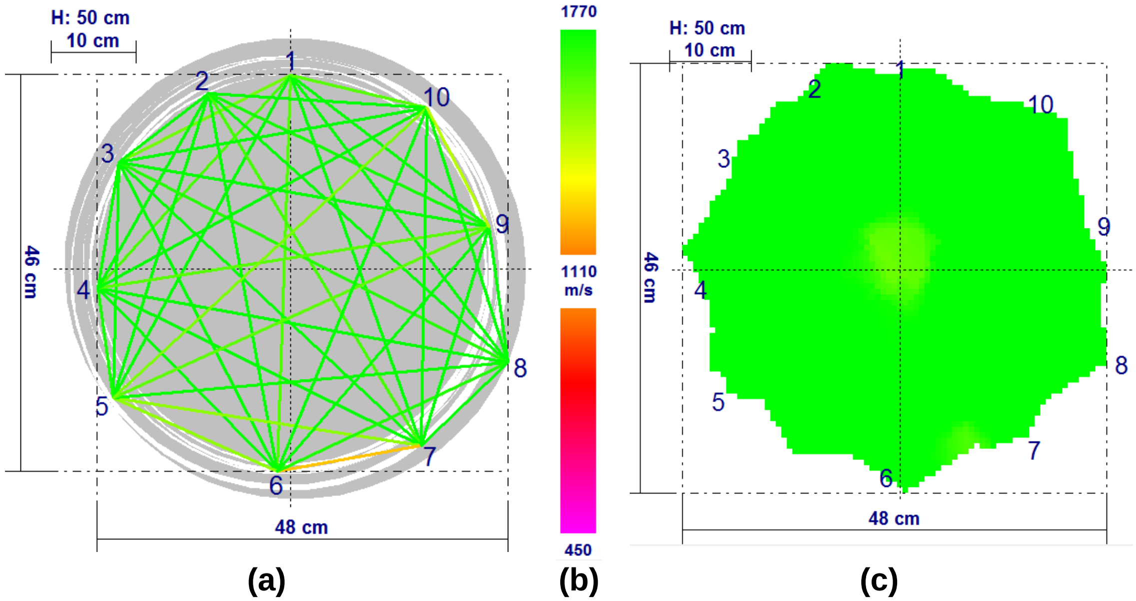


Fig. 18. The transmission of sound waves to the beech tree number 7, at the level of 50 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

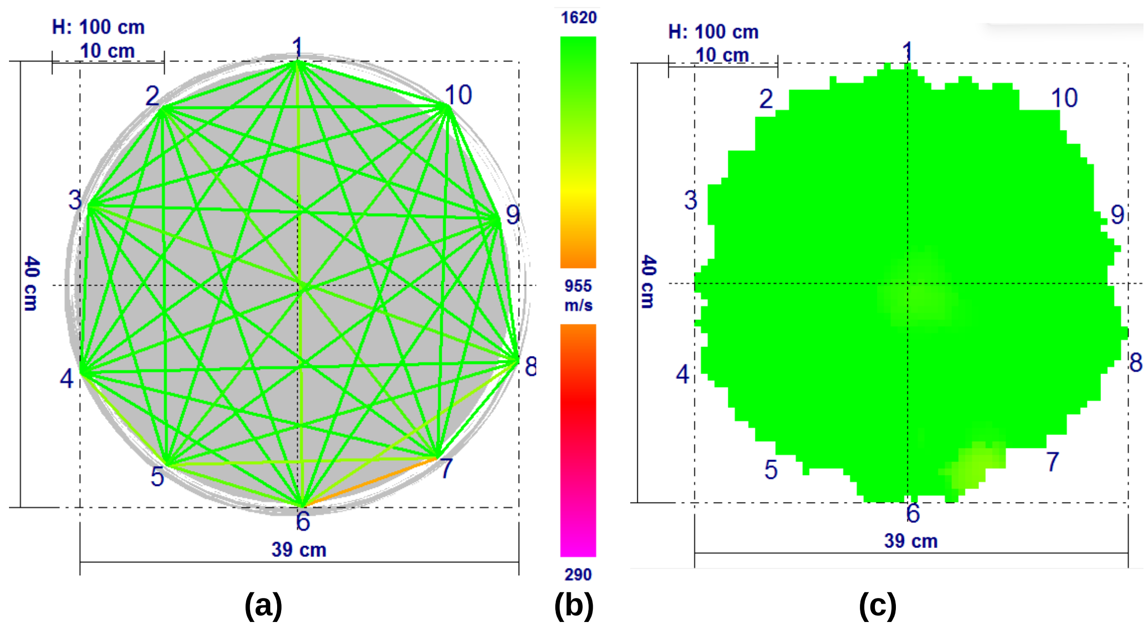


Fig. 19. The transmission of sound waves to the beech tree number 7, at the level of 100 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

Analyzing the speeds of sounds for each investigated section, it could be observed that the values smaller than 1000 m/s were registered only in neighboring sensors. This is a situation mentioned also in other papers (Wang *et al.* 2007; Deflorio *et al.* 2008; Rinn 2014; Du *et al.* 2015; Musat *et al.* 2017).

The resistograph was used to evaluate the relative resistances to drilling for the sensor S_6 located at the first section (50 cm above ground). As could be seen in the resistogram (Fig. 20), the wood was healthy inside the trunk because there were variations between the latewood and earlywood within the annual rings. Although the first 15 cm of the resistogram exhibited quite low values of the resistances, especially in the first 7 cm, there could be seen variation inside the wood, which characterized some wood without problems, and these relatively low values of resistances could be generated by the development of the tree.

Even if the relative resistances to drilling did show little variation within the annual rings, there were differences between hardwood and earlywood (Fig. 20), and the overall view indicated a healthy wood. So, these kinds of variations of the relative resistances to drilling could be characteristic for the beech trees in the study area.

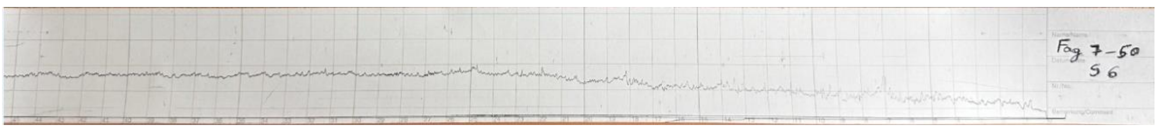
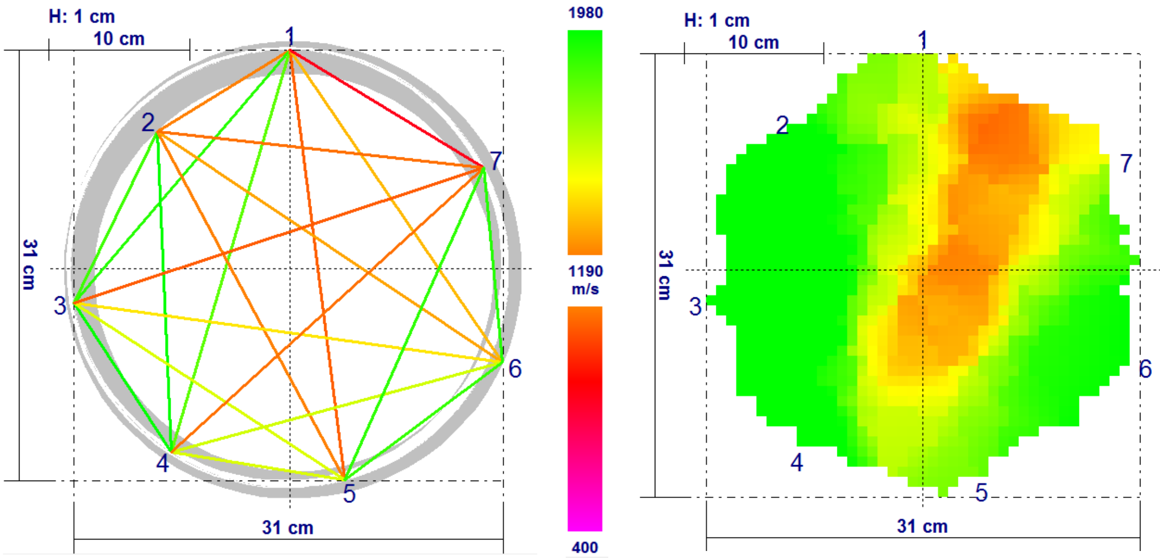


Fig. 20. The resistogram made and the growth core extracted from the beech tree number 7, from the direction of the S_6 sensor at the 50 cm level

The beech tree number 16 was almost unaffected by the fire.The only defect appeared in the western part of the trunk, at the bottom, and it did not have much extension, being surrounded by scar tissue (Fig. 21).

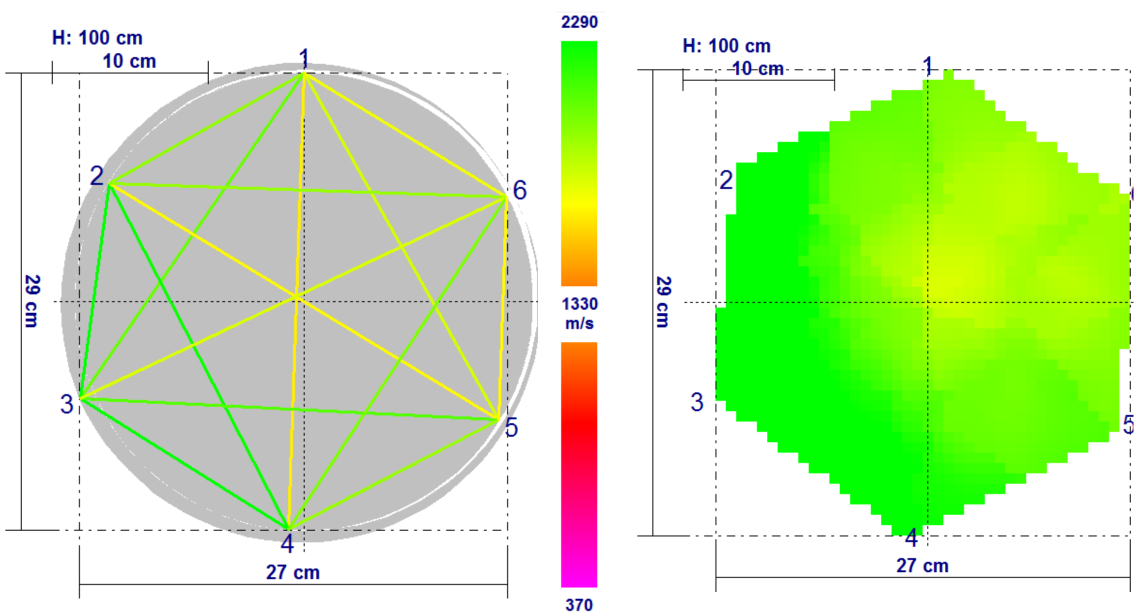
Fig. 21. The aspect of the beech tree number 16 at the visual assessment

Instead, a closed frost-crack appeared on the north-west direction (Fig. 21), whose effect seemed to be identified on the tomogram as well (Fig. 22c). This effect is illustrated in the sense that on the direction of the frost-crack, between the sensors S_{7-1}, an area of orange color appeared, framed by yellow, which characterizes the wood from the surface towards the center of the trunk, indicating the structural changes and internal inhomogeneities of the wood.The image with the transfer speeds of sounds through wood (Fig. 22a) reconstructed by the tomograph based on the average speeds indicated low values between the sensors S_{1-2} = 751 m/s, S_{2-1} = 829 m/s, and S_{6-1} = 996 m/s. It is noteworthy that almost all the sound waves going from the sensor S_7 to the sensors S_1, S_2, and S_6 were very low, oscillating from 405 to 901 m/s.



(a) (b) (c)

Fig. 22. The transmission of sound waves to the beech tree number 16, at the level of 50 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram



(a) (b) (c)

Fig. 23. The transmission of sound waves to the beech tree number 16, at the level of 100 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

At the level of 100 cm above the ground, the tomogram (Fig. 23a) indicated wood with better characteristics from a structural point of view, even if on the same side of the trunk some internal irregularities persisted, so also in the area near the frost-crack. Related to the sound propagation speeds through wood, low values appeared between the sensors S_{1-2} = 844 m/s and S_{5-6} = 381 m/s. In the rest, the speeds were higher than 1100 m/s, with even a speed of 2216 m/s being recorded between the sensors S_{2-3}.

The resistogram made in the direction of the sensor S_7 (Fig. 24) at the level of 50 cm, practically right next to the frost-crack, indicated important variations and big relative resistances in the first 8 cm, after which, for about 1 cm, there was a sudden decrease in the relative resistances to drilling. A comparison of the growth core extracted from the same area revealed that the first part of the wood was healthy, after which, in the area of reduction of relative resistances to drilling, the wood was brown, indicating a certain state of degradation.

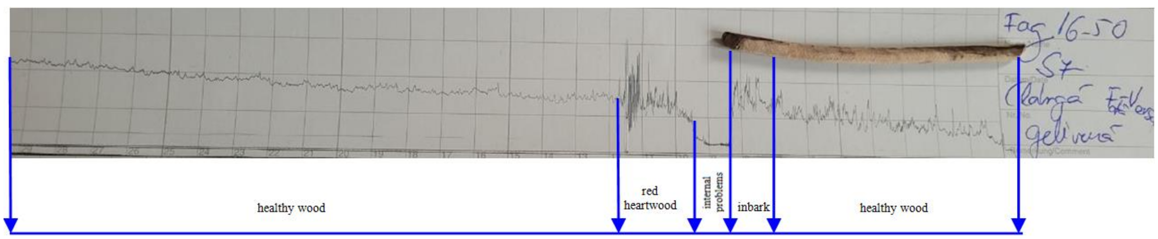


Fig. 24. The resistogram made and the growth core extracted from the beech tree number 16, from the direction of the S_7 sensor at the 50 cm level

For the resistogram made in the direction of the sensor S_7, at the level of 100 cm (Fig. 25), it was observed that at the beginning, in the first 7 cm, the relative resistances to drilling were quite a bit lower, compared with the rest of the resistogram, but then they increased. In addition, the existence of oscillations did not indicate the destruction of the wood structure, so the wood was healthy.

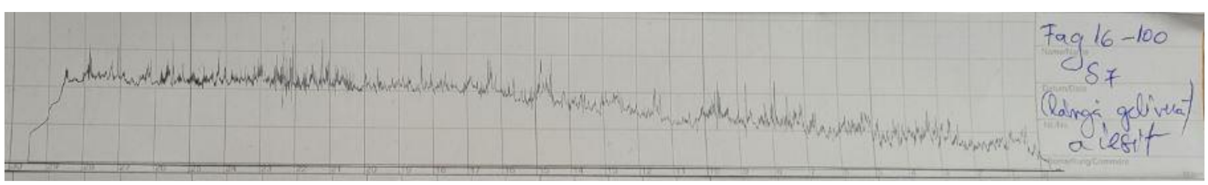


Fig. 25. The resistogram made and the growth core extracted from the beech tree number 16, from the direction of the S_7 sensor at the 100 cm level

The beech number 19 showed dead wood, dry and cracked bark at the base of the trunk, in the north-east direction, but the wound was surrounded on the sides by scar tissue (Fig. 26). At the 50 cm level, between sensors S_{1-2-3}, the trunk showed visible signs of fire that consisted of fallen bark from the trunk, dead wood, and a beginning of decay. Even if these defects could not be accurately identified on the tomogram (Fig. 27c), the image being colored in green, the transfer speeds of the sounds between sensors S_{1-2-3} showed small values (S_{1-2} = 670 m/s, S_{2-1} = 904 m/s, S_{3-2} = 823 m/s, S_{3-4} = 816 m/s, S_{4-5} = 775 m/s, and S_{7-6} = 384 m/s). All of these speeds were recorded more on the circumference of the trunk, between the neighboring sensors (Fig. 27a), a fact that did not lead to coloring the tomogram in other colors.

Fig. 26. The aspect of the beech tree number 19 at the visual assessment

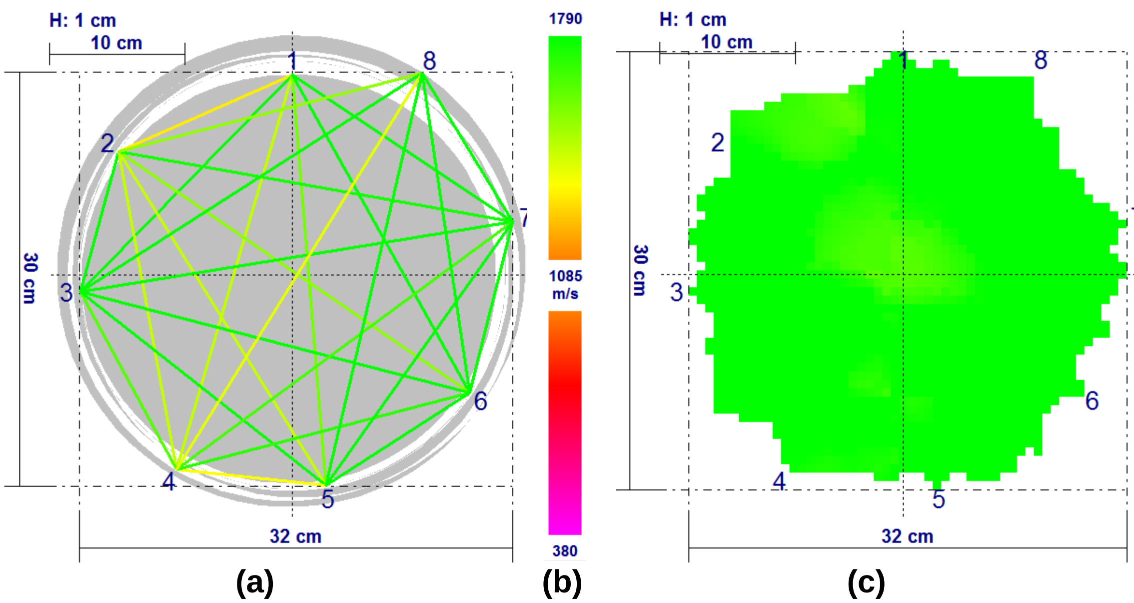


Fig. 27. The transmission of sound waves to the beech tree number 19, at the level of 50 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

At the 100 cm level, the tomogram (Fig. 28c) indicated only wood without irregularities.However, analyzing the speed matrix between the sensors and the colors of the connecting lines between them (Fig. 28a), there were speeds lower than most of the values (S_{1-2} = 812 m/s, S_{2-1} = 943 m/s, S_{2-4} = 793 m/s, S_{3-2} = 828 m/s, S_{4-2} = 663 m/s, S_{6-1} = 392 m/s, S_{6-5} = 993 m/s, S_{7-1} = 916 m/s, and S_{7-6} = 970 m/s), which appeared between 1000 and almost 1600 m/s. This means that the degradation at the 50 cm level (most affected by the fire, as seen on the trunk) was also affecting the upper regions, although not with the same intensity and that the degradation has spread from the bottom upwards.

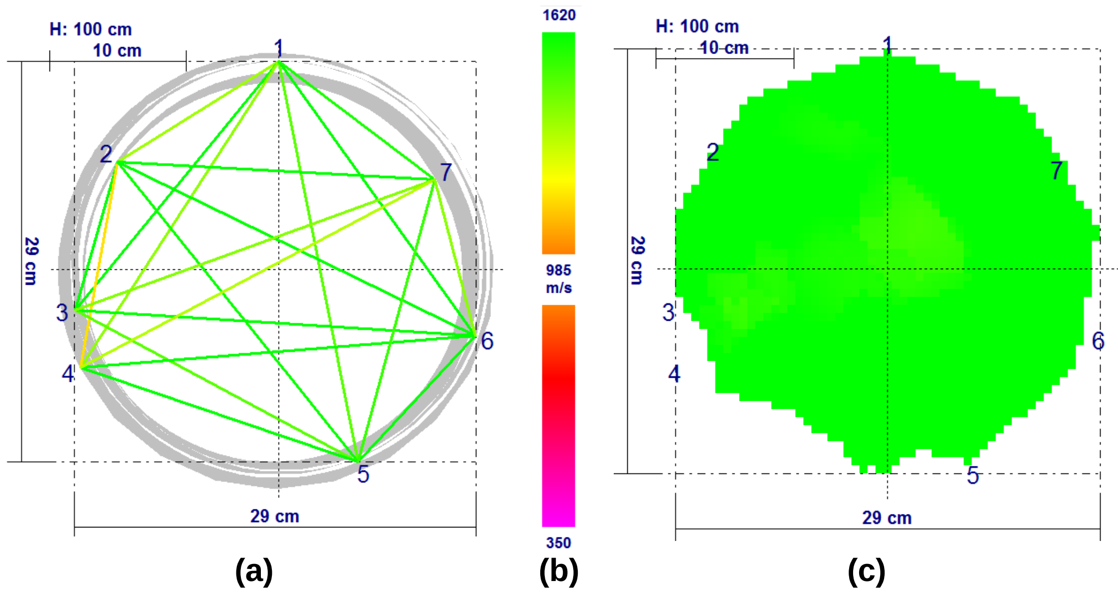


Fig. 28. The transmission of sound waves to the beech tree number 19, at the level of 100 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

Analyzing the resistogram made in the direction of sensor S_2, at the level of 50 cm (Fig. 29), it is apparent that the first centimeter of the thickness of the trunk was affected by rot. The resistogram shows very low relative resistances to drilling and no relevant oscillations, but the effects of degradation could be seen much more easily on the growth core. Then, in the area between 1 and 9 cm of the sample length, larger variations in the relative resistances to drilling were visible, after which they began to increase towards the center of the trunk. On the growth core, the wood looked healthy, and the relative resistances varied within the annual rings. The relatively low values of the resistances from the first 9 cm could be attributed to the resistogram and to the growth core, which were extracted from a portion with dead wood, so the wood, even though healthy, had different properties compared with the healthy wood.

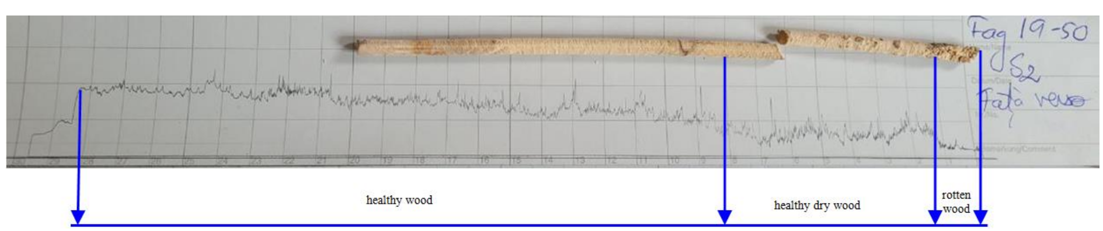


Fig. 29. The resistogram made and the growth core extracted from the beech tree number 19, from the direction of the S_2 sensor at the 50 cm level

The tree number 21 showed signs of fire on the trunk, in the east-southeast direction. The damage was more precisely in the direction of sensor S_4 at the level of 50 cm above the ground. These effects consisted of fallen bark over a narrow but long area, of several meters. In addition, it was found that from the height of 1.80 m, various fruiting bodies of some xylophages fungi that attacked the wood appear in the affected area, despite that the tree tried to cover the affected area, along the wound, which was found as scar tissue (Fig. 30).

Fig. 30. The aspect of the beech tree number 21 at the visual assessment

The tomogram performed at the 50 cm level (Fig. 31c) indicated lower sound transfer speeds through wood in the area between the sensors $S_{2-1-8-7-6}$, on almost ¾ of the surface of the investigated cross-section, *i.e.*, in the area not affected by the fire, while the area between sensors S_{3-4-5} appeared colored in green, requiring high transfer speeds of sounds through wood (Fig. 27b).

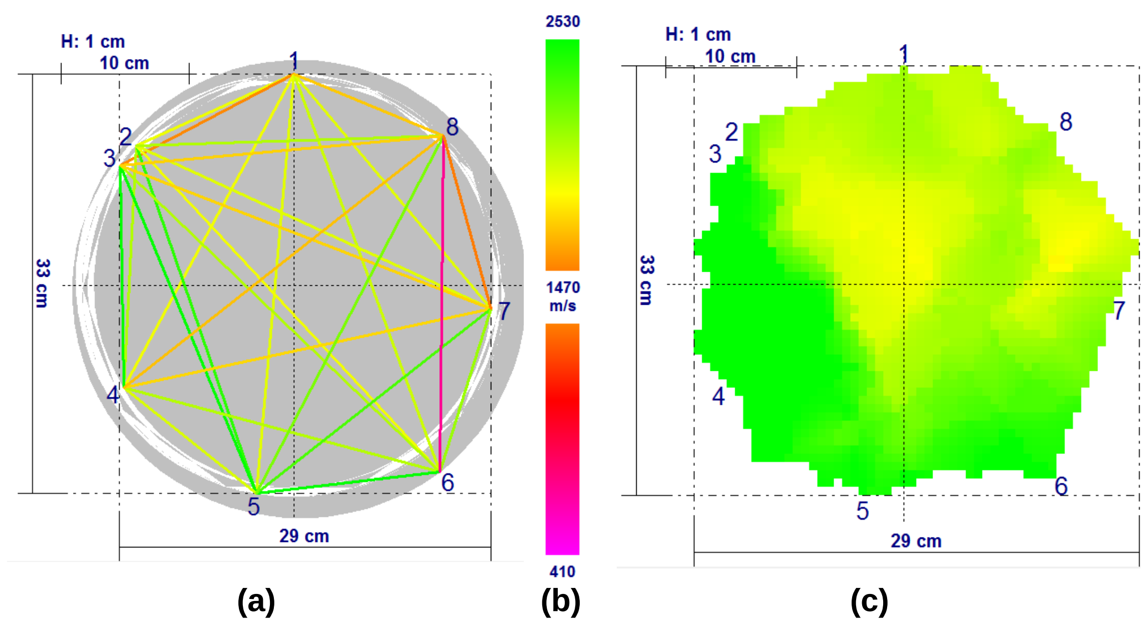


Fig. 31. The transmission of sound waves to the beech tree number 21, at the level of 50 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

In contrast, the speeds recorded between sensors S_{6-7-8} have low values (S_{7-6} = 420 m/s, S_{8-6} = 506 m/s, S_{6-7} = 527 m/s,and S_{6-8} = 528 m/s), illustrated in the image with the transfer speeds of sounds between pairs of sensors (Fig. 31a) with shades of yellow, orange, and even purple.

At the 100 cm level (Fig.32a), a value of 360 m/s was recorded between the sensors S_{7-6}, but this may be due to a curvature of the trunk in that area that probably influenced the mode and speed of transmission of a sound.Three more values between 950 and 1000 m/s appeared, then all speeds were greater than 1000 m/s, making the tomogram (Fig.32c) colored entirely in green, indicating wood without internal irregularities.

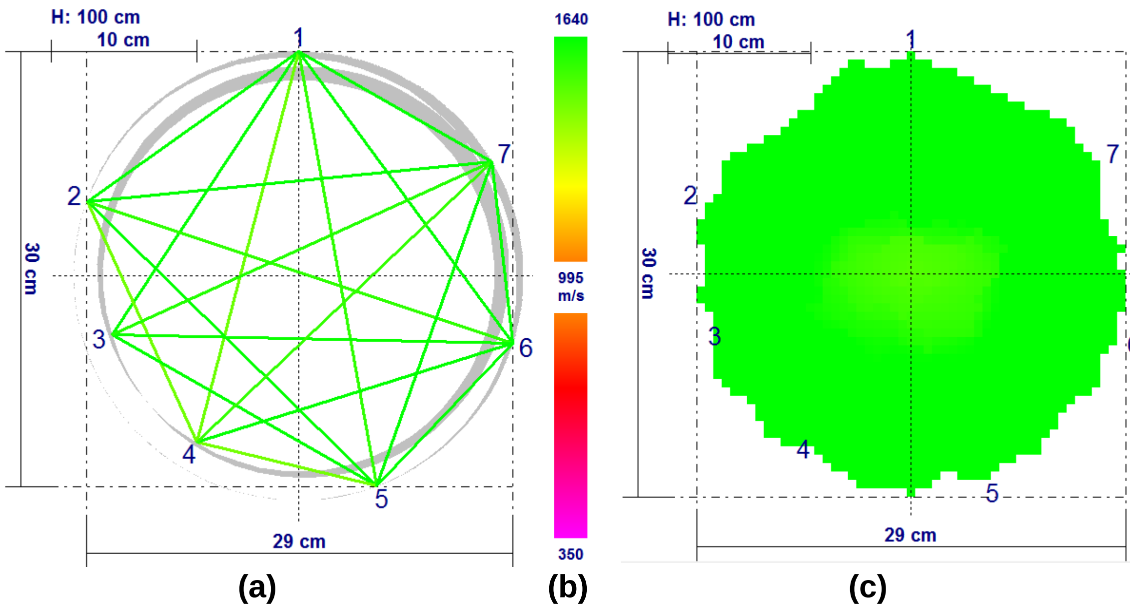


Fig. 32. The transmission of sound waves to the beech tree number 21, at the level of 100 cm: a) the links between the sensors; b) the speeds scale; and c) the tomogram

The resistogram made on the direction of the sensor S_8, at the level of 50 cm above the ground (Fig. 33) showed on the first 10 cm (that is one third of the diameter of the investigated section between the sensors S_{8-4}), a series of violent oscillations, indicating the relative resistances that the drill encountered in the first part of the trunk thickness. Then, these resistances, although increased in value, no longer registeredimportant oscillations after about 13 cm of the length of the resistogram.Thus, the wood was healthy and probably these were the normal resistances for the beech trees located in the study area. The big variations within the annual rings from the first 13 cm of the resistogramwere identified also by the tomograph, where the areas delimited by the sensors $S_{1-2-5-6-7-8}$ was colored in different shades of yellow, but the sounds speeds were bigger than 1500 m/s.

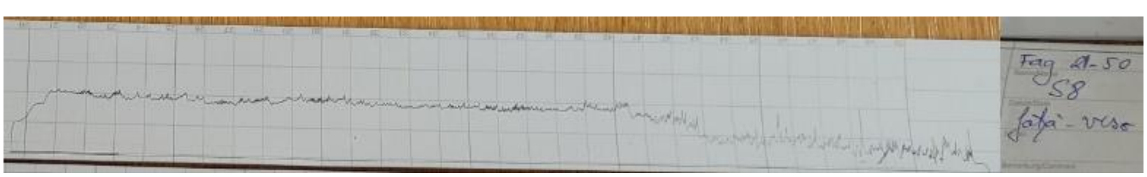


Fig. 33. The resistogram made and the growth core extracted from the beech tree number 21, from the direction of the S_8 sensor at the 50 cm level

In summary, it could be said that the tree, through its self-defense system, caused some changes of the wood structure inside the trunk (Beldeanu 2001, 2008; Lunguleasa 2004), which led to an increase in the transfer rates of sounds through the wood, to higher relative resistances to drilling, but there was almost no variation between the earlywood and latewood from the annual rings.

DISCUSSION

Wood in trees damaged by fires is subject to major loss in its value. This can be attributed to the intensity and type of fire and to the passage of time. In addition, particularly important economic losses are reached, both by reducing the volume of working wood that can be used in industry (Lynch 2004; Rodríguez y Silva *et al.* 2012), as well as the fact that these stands continue to exist in poor conditions, surviving with difficulty dueto the disturbing factors, including xylophages fungi (Lunguleasa 2004; Beldeanu 2008). Economic losses are also due to the harvesting process performed before the exploitation age of stands affected by fire (Rodríguez y Silva *et al.* 2012). Conversely, if one were to wait until the age at which the largest volumes of wood with industrial use are obtained (Ciubotaru 1998), the economic losses could be total, due to the depreciation of the wood, which will not be proper to use even as firewood.

Modern techniques for assessing the internal quality of wood must be used by people with training in this regard, who know both how the devices work and the particularities of the wood that can influence the interpretation of the results (Wang *et al.* 2009; Feng *et al.* 2014; Wu *et al.* 2018). In this respect, Musat (2023) mentions that the interpretation of the tomograms must be done in accordance with the speeds scale of the determination, because otherwise wrong conclusions can be drawn about the state of the wood inside the trunk. The author (Musat 2023) observed that, if the section analyzed with the tomograph traverses both a portion of the trunk and a raised branch, the transfer speeds of the sounds through the wood in the branch are much higher compared to those in the trunk, which caused the tomogram to be colored in green only in a certain area.The superficial interpretation of the tomogram could have led to the idea that in the area with orange there was a pronounced degradation of the wood. In contrast, when interpreting the tomogram in accordance with its own speeds scale, it was observed that the area with green corresponded to speeds over 3000 m/s, and the remaining area in the tomogram corresponded to speeds over 1000 m/s, so in both situations the wood was healthy. Regarding the present research, a similar situation occurred, where for beech tree numbers 3 and 4, the tomograms and the images of sound transfer rates between sensors were brightly colored in shades of orange.This can mislead a less experienced operator, who might say that these colors clearly indicate wood in various stages of decay. The wrong interpretation of the tomogram could be possible because,in a broad sense, the shades of yellow, orange, and red correspond to wood that is decayed or with internal irregularities, characterized by slower rates oftransfer of sounds through wood (Feng *et al.* 2014).

Similar situations in which the tomograph does not depict or locate a defect correctly (as position and extent) were encountered in other studies (Wang *et al.* 2007; Wang *et al.* 2009; Liang and Fu 2012; Feng *et al.* 2014). Thus, Wang *et al.* (2007) mention that a sound wave developed in one direction can detect internal rot only if it occupies more than 20% of the entire section traversed by that wave.In the present research, the presence of rot was highlighted by the tomograph in situations where the structure of the wood was destroyed to a very large extent. Conversely, when the wood was in an early stage of decay, the tomograph could not truly illustrate the severity of the internal defect. This aspect can be attributed to the fact that the structure of the wood was not completely destroyed by the xylophages fungi (Martinis *et al.* 2004), especially because the speeds of propagation of sounds through wood are closely related to the physical properties of wood (Feng *et al.* 2014; Alves *et al.* 2015). Sound speed is known to be especially sensitive not only to the density and the moisture of the wood (Sandoz and Lorin 1996; Punches 2004; Beldeanu 2008; Deflorio *et al.* 2008; Lin and Wu 2013; Leboucher 2014; Wang *et al.* 2017), but also to the modulus of elasticity (Sandoz and Lorin 1996; Yamazaki and Sasaki 2010; Feng *et al.* 2014). In addition, the reconstructed tomograms suffer from some information distortion due to the directions of sound propagation through the wood reported relative to the direction of the fibers (Beldeanu 2001; Beldeanu 2008; Feng *et al.* 2014; Li *et al.* 2014). It is known that the highest transfer speeds occur in directions parallel to the fibers, followed by those where the sounds are transferred radially and only then by in which the sound are transferred tangentially to the annual rings (Beldeanu 2001; Lunguleasa 2004; Beldeanu 2008). Related to this aspect, it was found that lower transfer speeds of sounds were obtained between neighboring sensors, because they assume a tangential propagation of sounds with respect to the annual rings.

According to Du *et al.* (2015), the quality of the tomograms near the sensors is less accurate than that in the central part of the trunk. This could be justified by the fact that the sounds propagate with difficulty between neighboring sensors. One reason for that consists in the presence of various shape defects (grooves, root-swelling) or is due to the external characteristics of the trunk. Another reason can be based on the tangential angle between the sound propagation direction and the annual rings.This general finding could also be because at the periphery of the trunk there are fewer connections between the sensors traversing this area, compared to the central area, a very important aspect because the tomogram is reconstructed in relation to the average transfer speeds of the sounds between the sensors.

Referring to additional investigations conducted with the IML F-500 Resi resistograph and the Pressler drill, supplementary information was obtained regarding the quality of the wood inside the trunk.These techniques were chosen to provide clear evidence of the real state of the wood, as a function of location, knowing that although they provide unidirectional information (Rinn 1994; Câmpu and Dumitrache 2015; Proto *et al.* 2020), they can highlight areas with rot or areas where the wood is in various stages of decay (Wang *et al.* 2009).Both resistograms and growth cores more clearly indicated the condition of the wood inside the trunk, both in rotten wood and in different stages of decay, as is the case of beech trees no. 3, 4, and 16. In addition, the fungi that can lead to the destruction of the wood structure, leading to substantial differences in properties (Lunguleasa 2004; Beldeanu 2008; Deflorio *et al.* 2008). Therefore, the mode of action and the length of time until the effects are visible can vary.In this regard, Deflorio *et al.* (2008) stated that in beech, although the tomograms did not indicate the presence of fungi and decay in the stem, the wood samples highlighted these aspects, the reduction in wood density was more pronounced when attacked by certain species of fungi compared to others (Sandak *et al.* 2020).

In later analysis of the tomograms of the trees where the red heartwood was detected (the beech tree numbers 3 and 4), it was observed that the defect influenced the transfer speeds of the sounds through the wood by increasing the values. This aspect was also highlighted by Sandoz and Lorin (1996), who mention that sound propagation speeds through red heartwood differ from those in healthy beech wood. From another perspective, the presence of the red heartwood inside the trunk influenced the overall transfer speeds of the sounds between the sensors, which were higher if the sounds crossed the red heartwood. In contrast, speed transfersthat were less than 1000 m/s almost always occurred at neighboring sensors, as is the case of tree no. 7, or at those that did not require the sounds to cross the red heartwood area. In other words, the presence of red heartwood can lead to an “artificial” increase in the average speeds of the transfer of sounds through the wood, which in the end can affect the correctness of the tomogram reconstructed by the tomograph, leading to an erroneous idea about the health of the wood inside the trunk. This is why in the specialized literature (Tarasiuk*et al.* 2007; Siegert 2013; Feng *et al.* 2014) it is also recommended to carry out additional investigations, especially in the case of defects or external signs, which indicate an intense degradation of the wood.

Information obtained from the investigations on beech tree number 4, where the red heartwood was identified on the growth core, can be used for interpretation. Based on the surface/length occupied at the level of the analyzed section, the heartwood can lead to an artificial increase in the propagation speeds of sounds through wood. Conversely, if the area occupied by the red heartwood in the cross-section of the trunk is reduced, and the surrounding wood is degraded, with the structure destroyed by fungi, the heartwood substances accumulated in the wood (Câmpu 2010; Câmpu and Dumitrache 2015), with all their properties to increase the density and the resistance of wood (Beldeanu 2001; Beldeanu 2008; Lunguleasa 2004). However, they cannot supplement the excessive decay of the wood by fungi.This fact makes the tomogram indicate lower sounds propagation speeds, so an image that corresponds more to reality.

An aspect that must be mentioned occurs in beech tree number 16, which presented a closed frost-crack in the western part, towards the base of the trunk. The frost-crack (Ciubotaru 1998; Beldeanu 2001; Câmpu and Dumitrache 2015) is a crack that mainly affects deciduous trees, with a radial arrangement, developed along the trunk, which occurs in winter due to the stresses generated by the contraction of the wood at the strong and sudden drop in temperatures (Beldeanu 2001, 2008; Câmpu and Dumitrache 2015). As a result of the wood’s tendency to cover the wound, the frost-crack is accompanied by scar tissue with growths that seem to influence the transfer speeds of sounds through the wood. Thus, the existing interruptions in the wood, due to the frost crack, whether it is closed or not, are reflected by lower transfer speeds between the sensors, thus in a coloring of the tomogram it is represented in shades of orange in the respective area, between sensors S_7 and S_1.This may support the statement from the literature (Garrett 1997; Brancheriau*et al.* 2012; Lin and Wu 2013; Du *et al.* 2015) according to which in healthy wood the sounds propagate in a straight line, leading to high transfer speeds, whereas in wood with defects and internal gaps, in case of interruptions in the wood structure, the sounds bypass the respective areas, so that the speeds are lower (Lin and Wu 2013; Feng *et al.* 2014; Du *et al.* 2015).

CONCLUSIONS

1. The trees showed serious signs of degradation based on visual inspection, which let the pathogens enter the trunk and led to the destruction of the integrity of the wood.

2. When the fire affected large parts of the trunk and roots, the trees were not able to close the wounds and the degradations became bigger over time, as could be seen in tree no. 4.
3. The degraded wood areas identified by the tomograph seemed smaller in extent compared to the real condition of the wood illustrated by the resistograph or observed from the outside of the trunk.
4. The presence of decay was highlighted by the tomograph at the real level of severity only in the situation when the wood's structure was destroyed to a very large extent.
5. If the low transfer speeds of sounds through wood represented a small share of the total number of values, they did not have the ability to noticeably change the tomogram, which also happens in the case of low speeds recorded between pairs of nearby sensors.
6. The red heartwood can increase the sounds speeds through the wood, as is the case of tree no. 2, and lead to a sudden increase in relative resistances to drilling, as in the case of trees no. 2 and 4.
7. The tomograph can identify the presence of the frost-crack inside the trunk, based on the structural changes and the internal irregularities due to the presence of the defect, as can be seen at tree no. 16.
8. The resistograph provides more accurate information about wood with internal defects, especially in the case of decayed wood, when do not appear any more the differences in relative resistances to drilling between latewood and earlywood.
9. Although resistograms and growth cores can more precisely indicate the real state of the wood inside the trunk, the information provided by these techniques is limited with respect to location. Thus, for an overall picture, several determinations must be made, which could represent a danger for the further development of the tree.

Conflict of Interest

The author declares no conflicts of interest.

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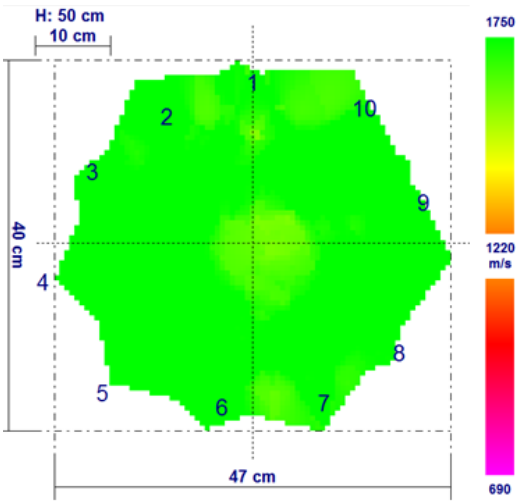
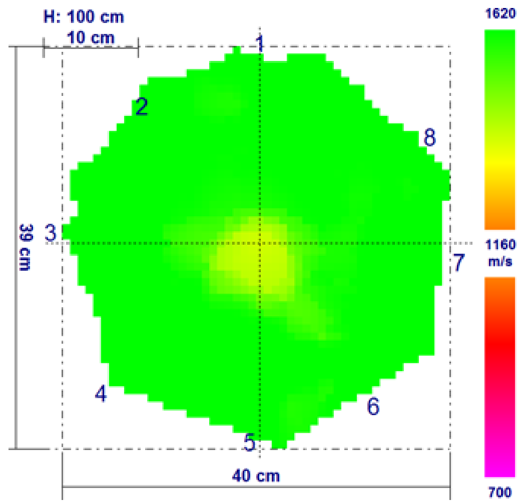
DOI: 10.15376/biores.19.4.7530-7565

APPENDIX

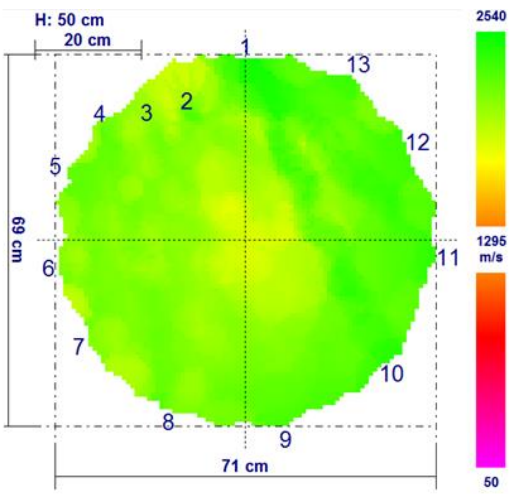
All the tomograms obtained for the investigated beech trees



Tree no. 1_50



Tree no. 1_100



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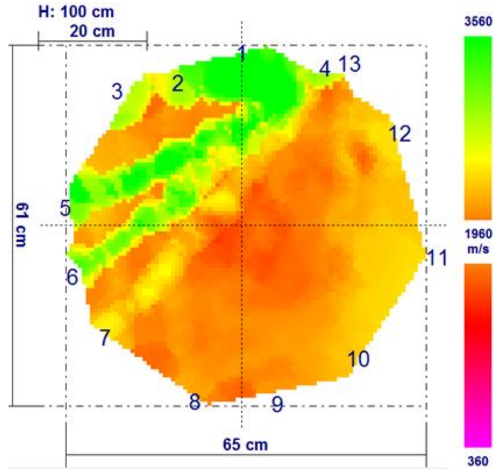

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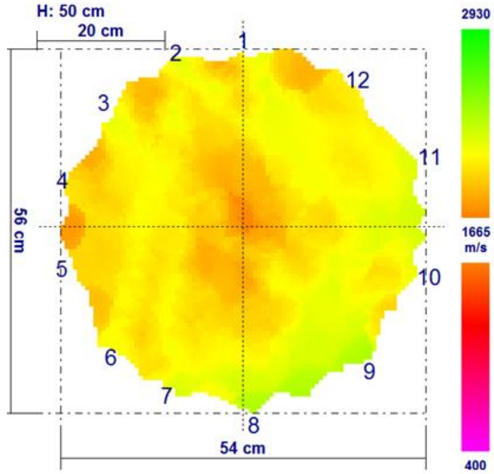
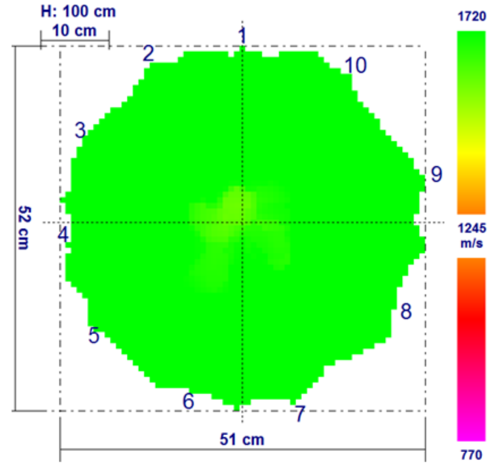
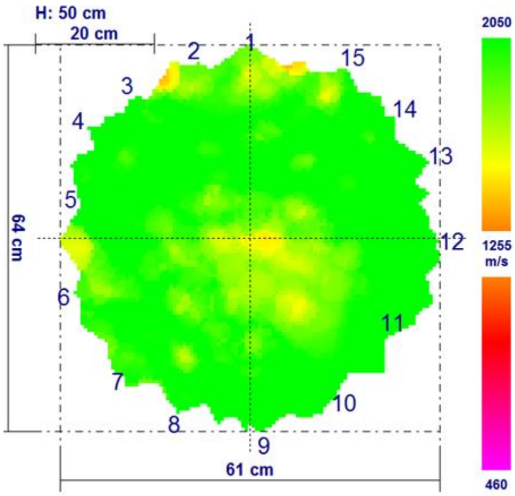


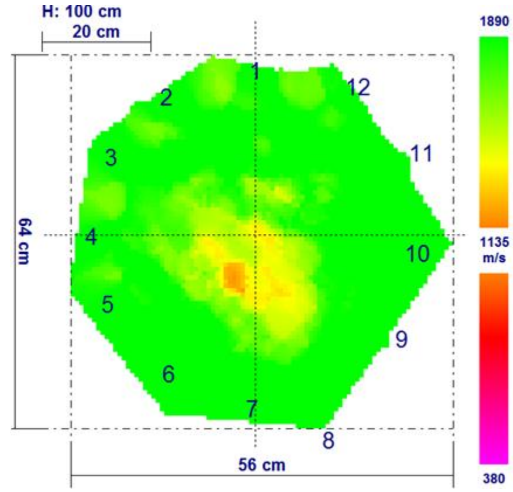
Tree no. 3_50



Tree no. 3_100



Tree no. 4_50



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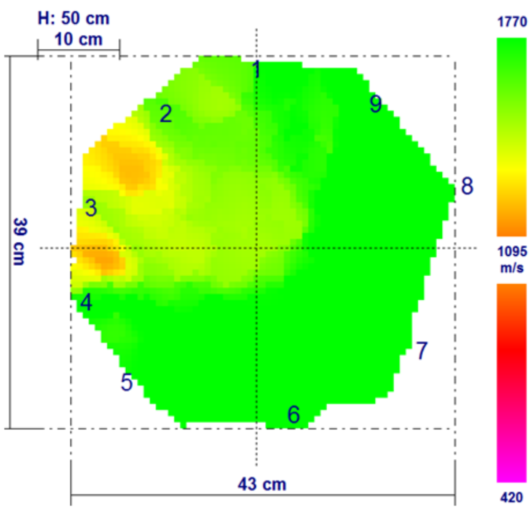

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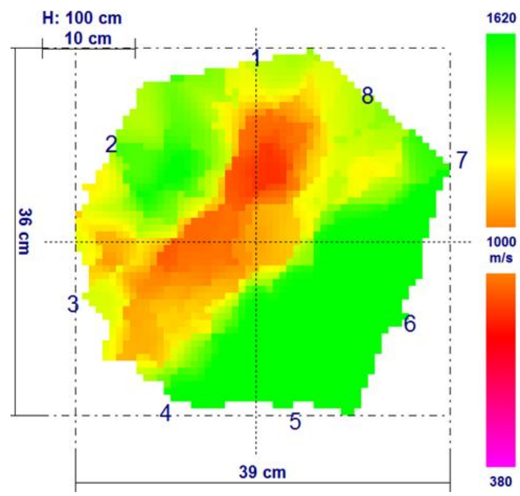
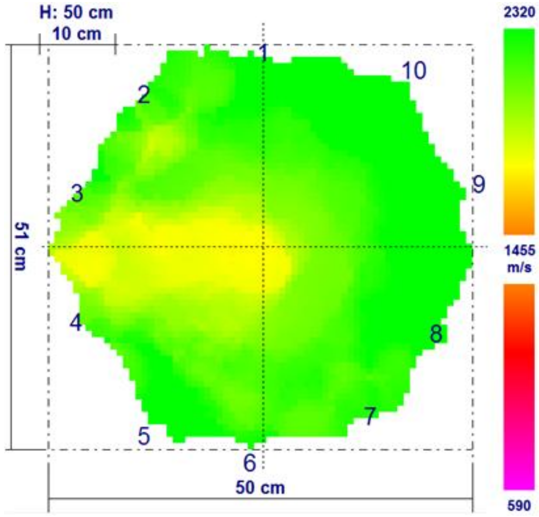


Tree no. 5_100



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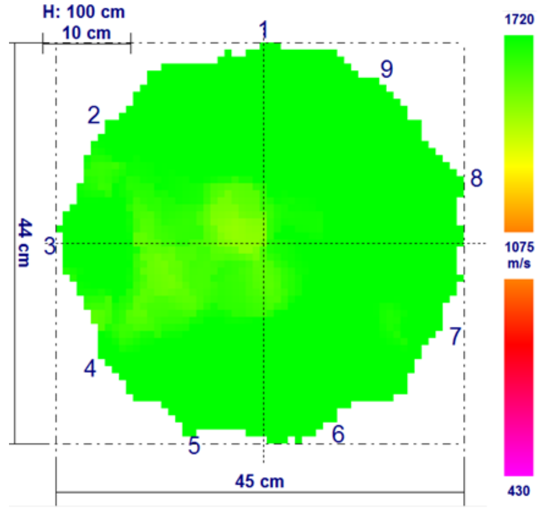

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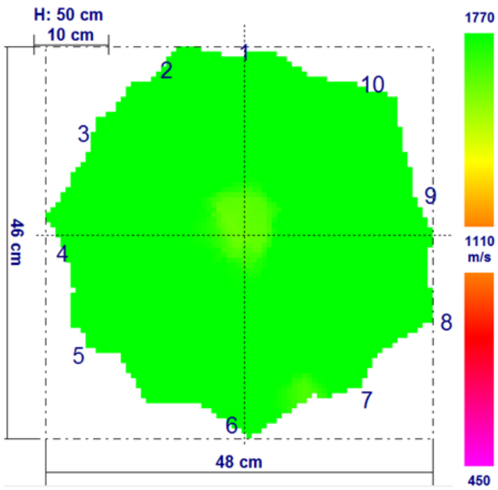

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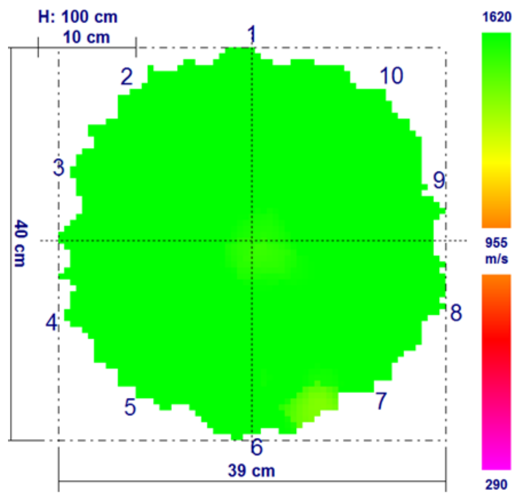

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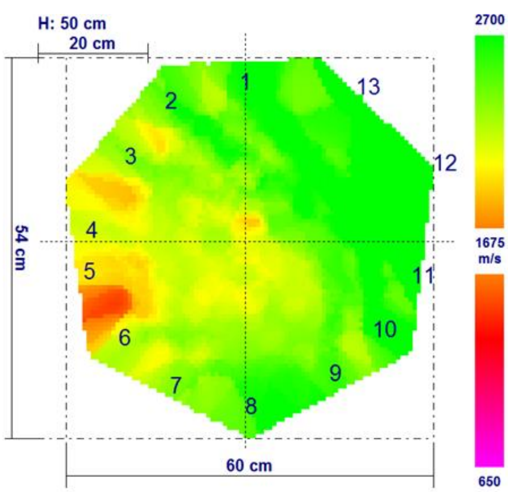

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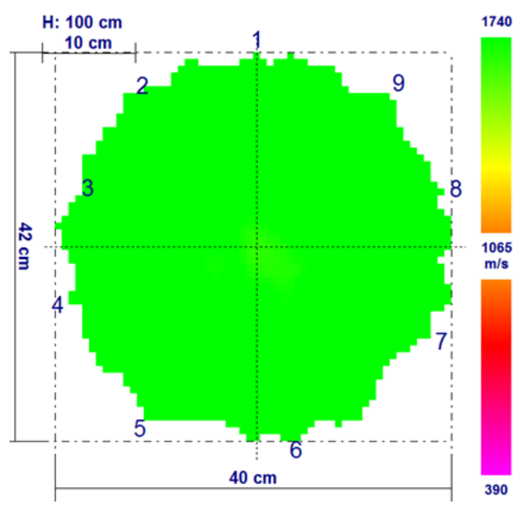

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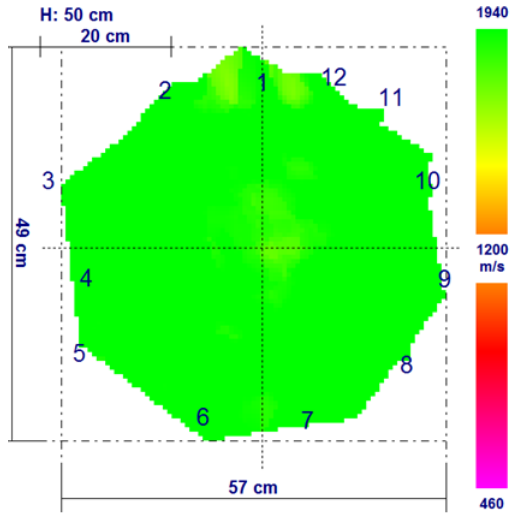

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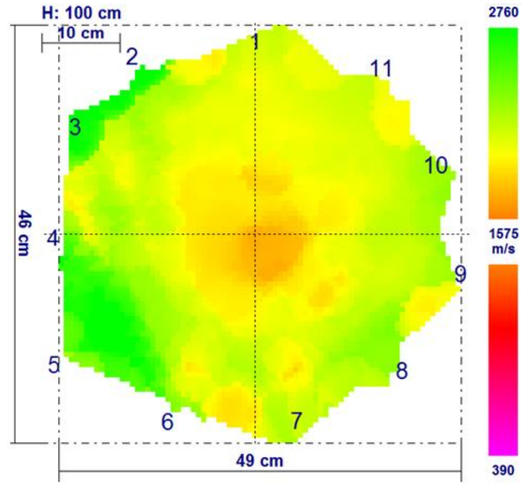

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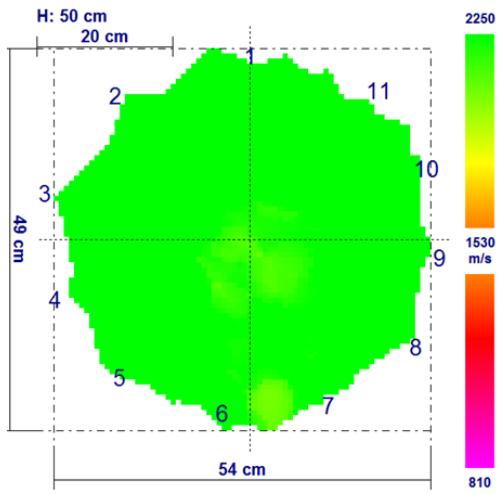

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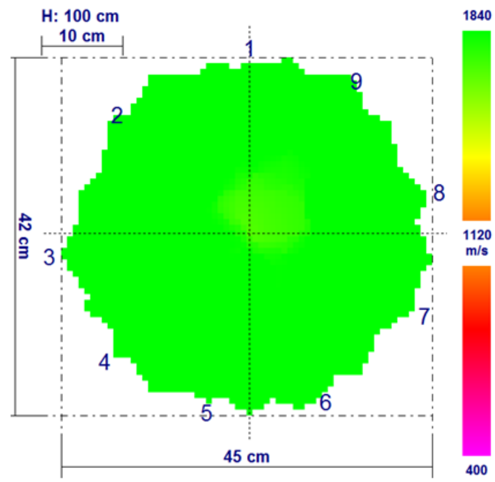

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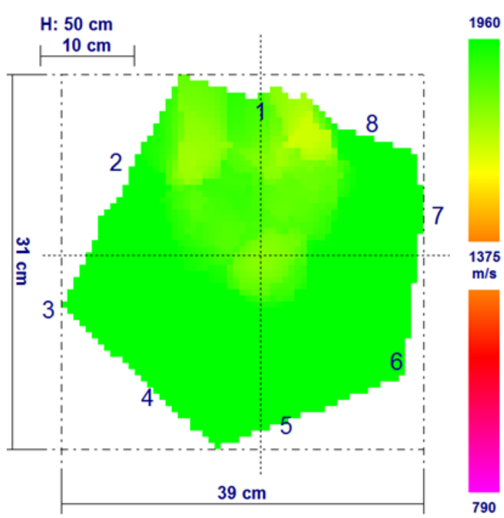

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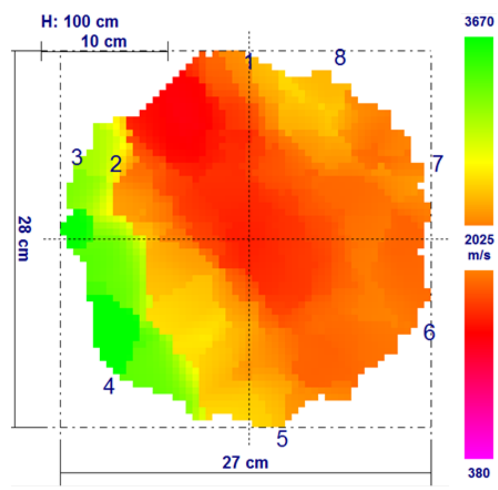

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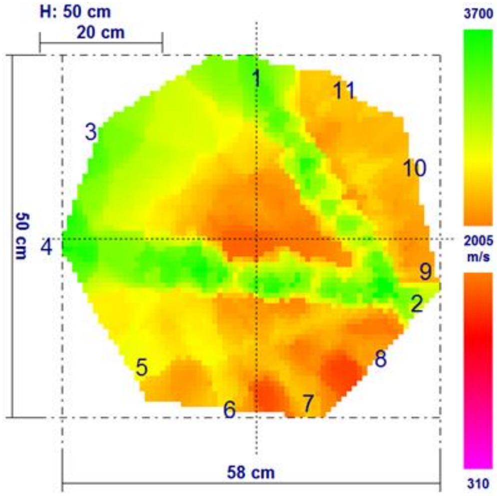

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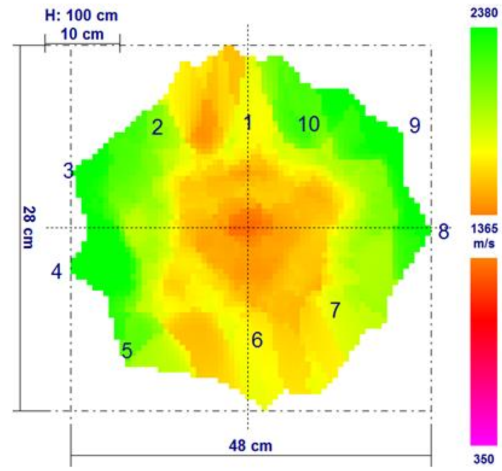

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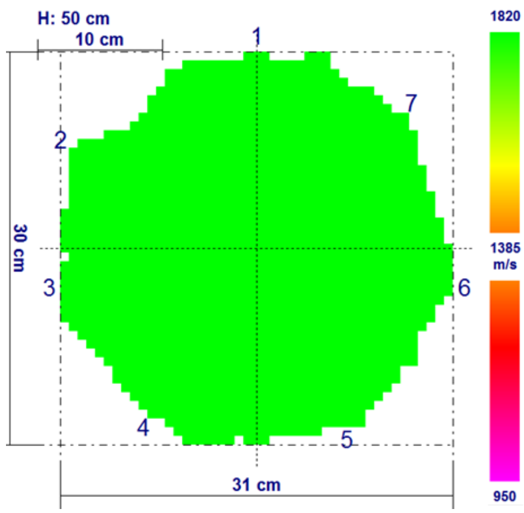

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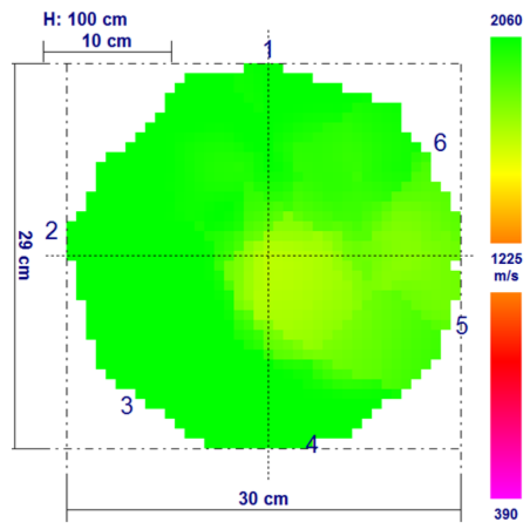

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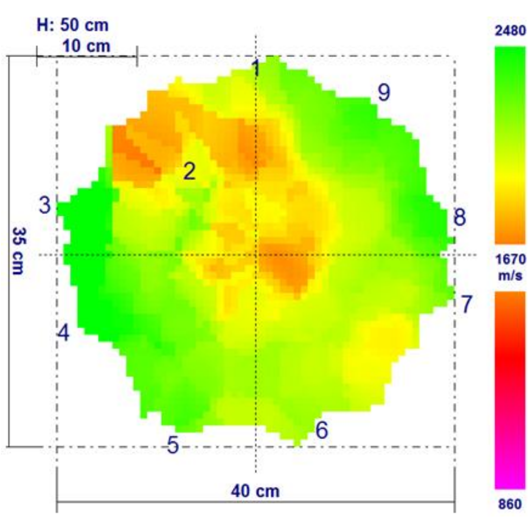

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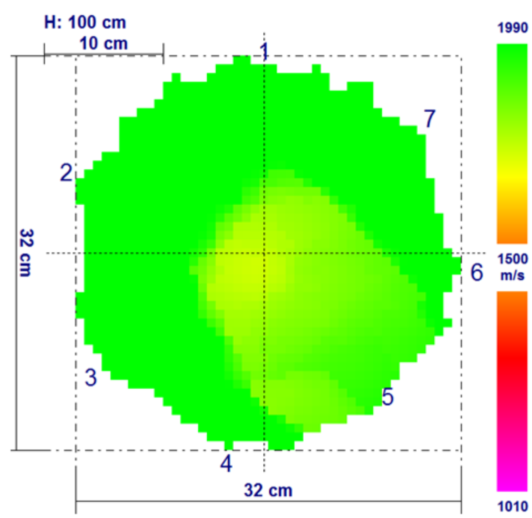

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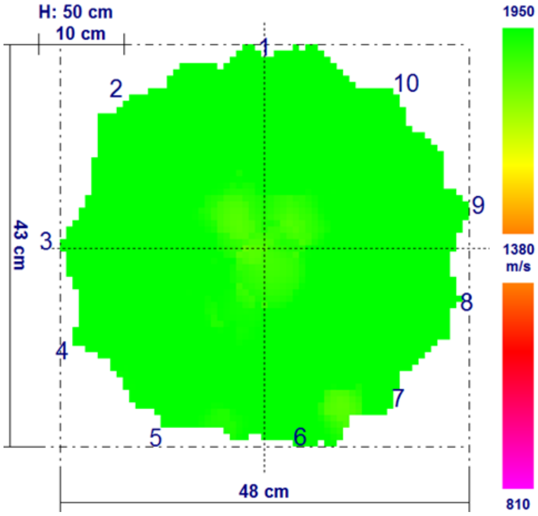

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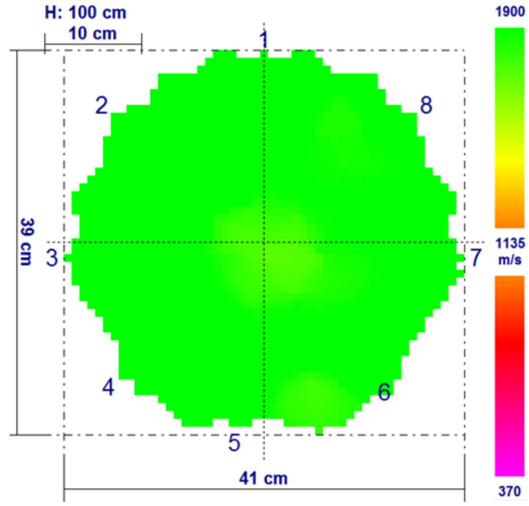

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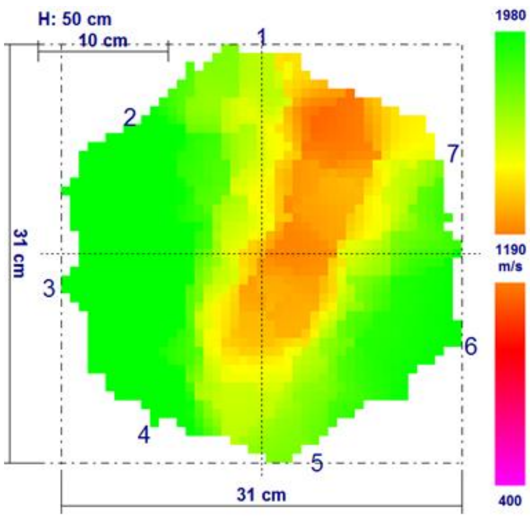

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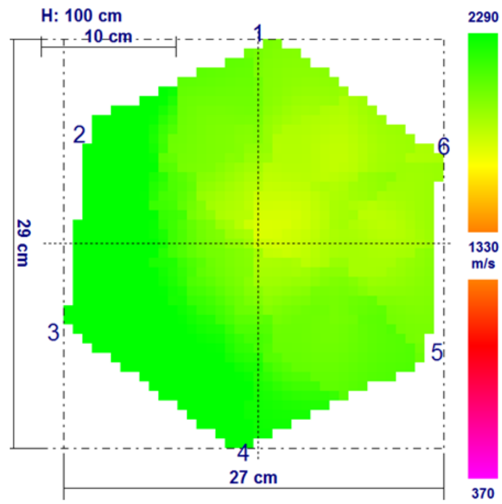

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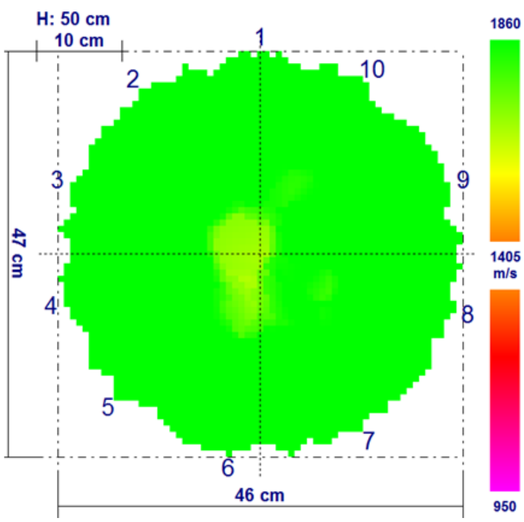

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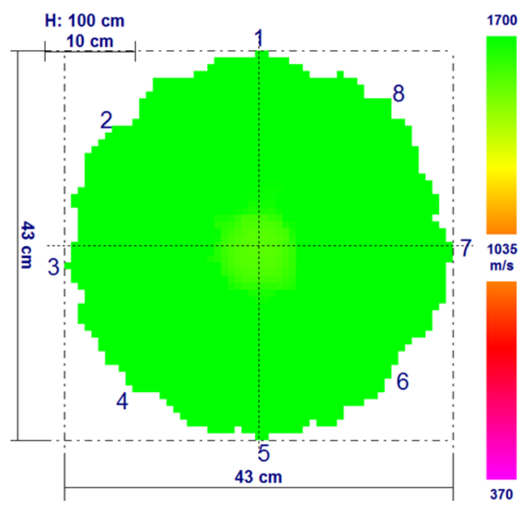

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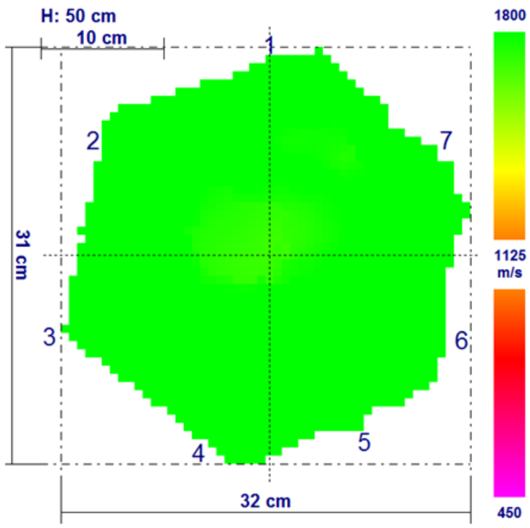

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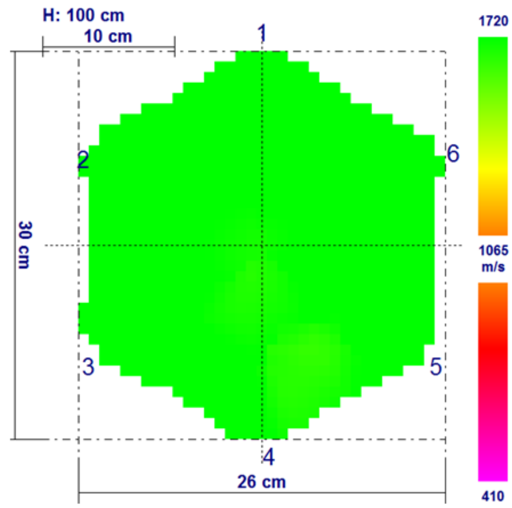

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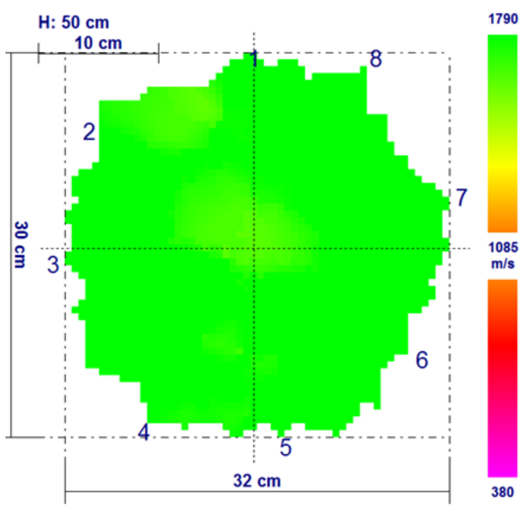

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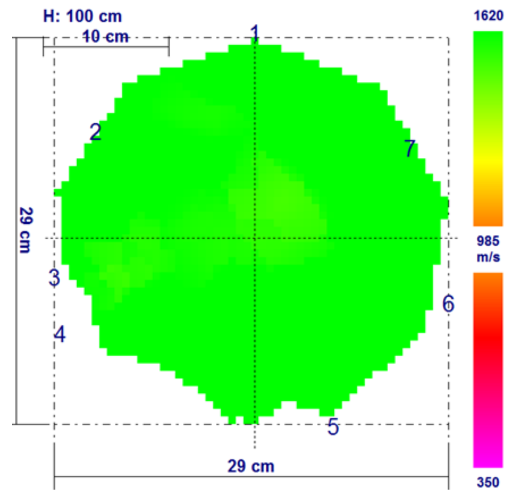

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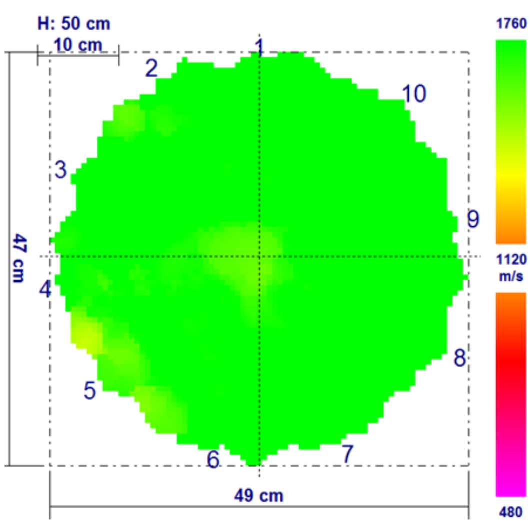

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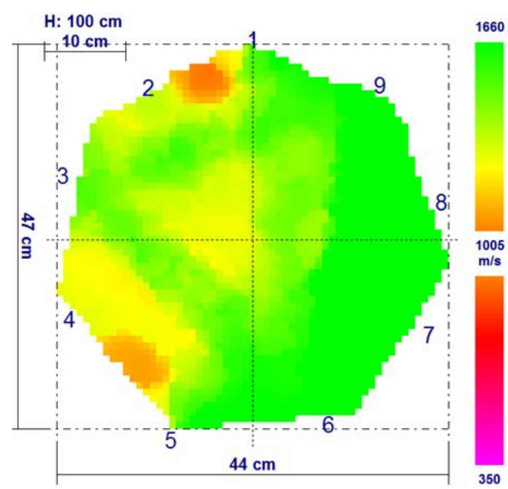

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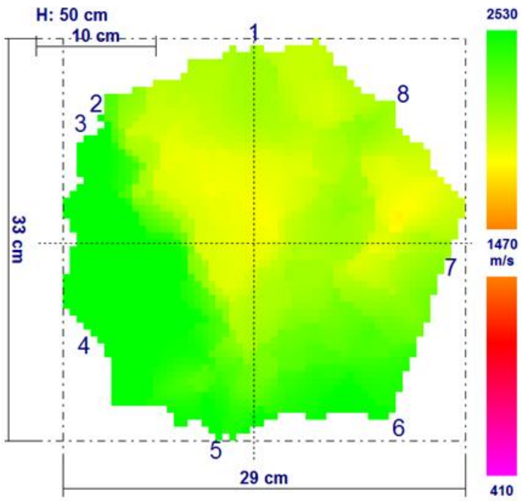

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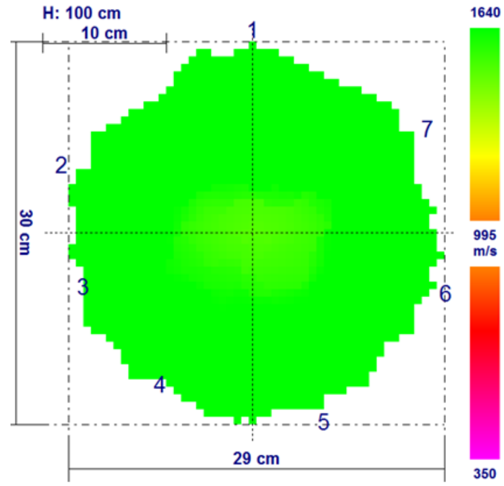

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