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Evaluation of internal wood condition in tree trunks using sonic tomography and electrical resistance tomography

Tamílis Emerick[1]✤, Angeline Martini[1], Marina Moura de Souza[2]

[1]Federal University of Viçosa (UFV), Campus Viçosa, Department of Forest Engineering, Viçosa, MG, Brazil
[2]Companhia Energética de Minas Gerais (CEMIG), Distribution, Belo Horizonte, MG, Brazil

TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Backgrounds: There are still uncertainties on how the data obtained from tomographs can affect tree failure risk evaluations. The aim of the study was to evaluate the internal trunk condition of *Spathodea campanulata* using sonic and electrical resistance tomographies. Forty-three sidewalk-planted, mature-stage individuals were assessed using PiCUS 3 and TreeTronic 3 tomography.

Results: Sonic tomographies detected internal wood decay in 27,9% of the individuals and the Electrical resistance ones detected 30,2%, due to sensitivity to different types of anomaly, explained by different operating principles. Five individuals showed differing results between the two types of equipment. Collectively, the tomographies revealed the following results: 55.8% of the trees had good internal conditions, 6.3% demonstrated decay, 16.3% demonstrated early stages of decay, and 11.6% demonstrated advanced stages of wood decay.

Conclusion: In conclusion, both tomographies provided significant information for diagnosing the internal condition of the trunk though their correct interpretation relies on the operator's level of expertise.

Keywords: Tree Risk; Tomograms; Internal tree decay; Wood decay.

HIGHLIGHTS

Five individuals presented results that were interpreted differently by the devices.
The use of both types of tomography favors the interpretation of the results.
The correct interpretation of tomograms depends on the operator's level of knowledge.
The use of devices generates a more accurate diagnosis of the nature of the tree defect.

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✤Corresponding author: tamilis.emerick@ufv.br
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INTRODUCTION

Assessing the potential failure of a tree is a systematic analysis aimed at identifying, analyzing, and assessing risk (Dunster et al., 2013). This assessment can range from a basic visual inspection to advanced internal investigations using sophisticated equipment (ANSI, 2011; Smiley et al., 2011), known as advanced assessments or level 3 assessments.

These methods may include aerial inspections, advanced techniques for detecting decomposition, and static/dynamic stability assessments of trees (Dunster et al., 2013; Koeser et al., 2017; Van Wassenaer and Richardson, 2009). They differ in terms of cost, underlying technology, level of invasiveness, and time (Johnstone et al., 2010; Leong et al., 2012; Nicolotti and Miglietta, 1998; Ouis, 2003).

There is no standardization of this type of evaluation in the world. Each country is dedicated to establishing a method which varies even at the municipal level (Bobrowski, 2016).

In Brazil, a recent effort created NBR 16246-3, a standard that deals with the requirements for the management of trees, shrubs, and other woody plants. Based on an American standard, the ANSI A300, it does not, however, reflect the reality of many Brazilian cities, which face challenges in terms of manpower and financial resources to do so.

In recent decades, CT methods have been considered the least invasive approach to assessing the internal condition of tree trunks in Level 3 assessments (Bucor, 2005). They are able to generate internal images of the tree without endangering its health – in a long-term perspective – (Brazee and Marra, 2019). Different types of CT scans can be generated depending on the method: Sonic CT scans (SoT), for example, measure the speed of sound waves as they travel through the wood. Electrical resistance tomography (ERT) scans, on the other hand, determine electrical conductivity through woody tissue (Brazee et al., 2011).

This equipment, when combined for tree risk assessment to know the internal condition of the wood and the specific stage of decomposition, proves to be very efficient, being the most advanced and innovative imaging technology today (Divakara and Chaithra, 2022).

Currently, a variety of tomography instruments in addition to those mentioned above, como Arbotom and Fakopp, have been used to evaluate, in two- or three-dimensional tomograms, the interior of the tree. These, however, have limitations related to low resolution of the generated image, limited surface flaw detection capacity, unreliable defect location (Qiu et al., 2019), and high cost.

Regardless of the challenges and operating principles, arborists increasingly recognize that this tool is useful in analyzing the internal condition of trees (Smiley et al., 2011) due to its reasonably accurate assessments (Johnstone et al., 2010).

However, it remains unclear how the information provided by these instruments can be used in assessments of the potential for tree failure. Existing methods for estimating the decrease in the mechanical strength of wood show inconsistent results when compared with each other (Kane et al., 2001; Koeser et al., 2017), as shown in the study with a sample of 70 arborists using analyses of different levels in the United States. In this case, there was a significant contrast between the risk classification assigned by the evaluator with the use of basic and more advanced analyses. However, the variation between observations using level III assessments was not as significant.

In this sense, it is understood that the use of more advanced techniques can eliminate part of the subjectivity of these analyses (Koeser et al., 2017).

The objective of this study was to analyze the internal condition of the trunk of individuals of *Spathodea campanulata* by means of sonic tomography and electrical resistivity, in order to verify the association between the results obtained with such equipment, considering the hypothesis that there is a strong correlation between their readings.

MATERIALS AND METHODS

Area and species of study

Sonic character and electrical resistance tomographies were used on 43 individuals of *Spathodea campanulate*. These individuals are used in the arborization of the campus in one of the main avenues of the Federal University of Viçosa, located in the city of Viçosa, in Minas Gerais, situated at coordinates 20°45’37”S and 42°52’04” W.

Known as Tulipeira – Africana or Spatodea, it is a tree of the Bignoniaceae family, native to Africa (Labrada and Diaz - Medina, 2009). It can reach more than 20m in height and its wood is characterized as “soft”, with a specific mass below 0.44g/cm3 (Vale et al., 2005).

The same individuals of *Spathodea campanulata* present on campus were previously measured by Silva (2019), who found an average DBH of 55.3cm and height of 13.4m. The exact age of these trees is not known, but it is believed that they were planted at the time of the university’s construction in 1926.

Equipment

The following equipment was used in this study to capture the sonic and electrical resistance tomographies: PiCUS® Sonic Tomography 3 and the TreeTronic 3, both of them provided by Minas Gerais Electric Power Company – CEMIG.

According to the German manufacturer, Sonic Tomography (SoT) measures the speed of sound waves in wood to detect decay and cavities in standing trees. The measurement is performed in a non-invasive manner. There is a correlation between the speed of sound in wood and its mechanical strength, which can then be used to infer the potential failures in trunks (Gocke, 2017). Its main limitation is related to the greater complexity and duration of the analysis (Papandrea et al., 2022).

The Electrical Resistance tomography (ERT), on the other hand, is an inspection method originally developed in the field of geophysics. It utilizes voltage and electric current, provided by electrodes placed on a surface. The objective is to locate resistance anomalies. It is primarily used in conjunction with the Sonic Tomography (SoT), allowing operators to analyze defect types and residual wall thickness more precisely, in addition to being highly sensitive in detecting early stages of decay (Gocke, 2017). Its main limitation is since the distribution of specific resistance is often altered inside the wood, due to the change of season and species, for example, requiring great practice from the evaluator (Papandrea et al., 2022).

CT scans were performed at a height of 20 cm above the base of the tree. It was a potentially risky point in case of decomposition (Smiley et al., 2000), where severe deterioration is common (Schwarze et al., 2000), as well as significant bending moments, when subjected to wind (Ennos, 2012). This was followed by: visual analysis of the trunk, circumference measurement, tree marking, and allocation of galvanized nails (5.1 cm long) – marked and inserted at depths beyond the bark, establishing contact with the sapwood. These nails were spaced between 15 and 20 cm and served as measurement points (MPs), where the sonic and electrical sensors and electrodes were inserted to collect the data.

The MPs were sequentially numbered, starting from MP-1. They were placed on the magnetic north (determined with a compass). Trunk diameter and species information were also collected at that moment. The manufacturer recommends that at least 3 points be analyzed.

The number of points was then inputted into the equipment so that the trunk geometry could be assessed using *PiCUS Calliper* device.

Following that, the sensors of the sonic tomography were positioned at each designated point, enabling the emission and reception of sound waves through the striking of the accompanying sonic hammer. It is recommended to perform approximately five hits at each point, ensuring that all points act as both transmitters and receivers of the wave.

Once the measurement is registered, the trunk geometry assessment is exported to the electrical resistance tomography. Here the number of measuring points (MPs) doubled compared to the previous stage. The allocation of electrodes is carried out at the respective points to enable current emission (Figure 1).

The data obtained was exported using Picus software. It generates an image using a color scale system used to represent the wood densities in that specific cross-section. The color scale designates intact and non-deteriorated wood as brown (higher relative velocities), while deteriorated wood is represented by green, pink, and blue colors (lower relative velocities, in decreasing order).

Regarding electrical resistance tomography, deviations from homogeneity in the wood yield a map of relative electrical resistivity, which is mainly correlated with moisture content but can also be affected by changes in ion concentration and/or cellular structure. The color-coded map designates red to indicate regions with higher electrical resistivity (lower conductivity) and gradually transitions through orange, yellow, green, and blue as the resistivity decreases (higher conductivity).

SoT and ERT data should be interpreted together to accurately predict the internal condition at each cross section of a tree, based on the following criteria (Brazee and Marra, 2020; Marra et al. 2018):

a) Brown-colored regions in the sonic tomography (indicating maximum wood density) and red-colored regions in the electrical resistance tomography (indicating absence of moisture) signify healthy wood conditions.
b) Brown-colored regions in the sonic tomography (indicating maximum wood density) and blue-colored regions in the electrical resistance tomogram (indicating presence of moisture) represent early-stage decay or bacterial moisture.
c) Blue/pink-colored regions in the sonic tomography (indicating reduced wood density) and red-colored regions in the electrical resistance tomography (indicating absence of moisture) indicate the presence of a cavity.
d) Blue/pink-colored regions in the sonic tomography (indicating reduced wood density) and blue-colored regions in the electrical resistance tomography indicate active wood decay.

Data analysis

In order to examine the correlation between the equipment utilized and the interpreted results, Pearson correlation coefficient was computed for the parameters measuring the degree of internal decay. For Dancey and Reidy (2006) point out a correlation (r) between 0.10 and 0.30 is considered weak, between 40 and 0.6 moderate and from 0.70 to 1 strong (Figueiredo Filho and Silva Júnior, 2009).

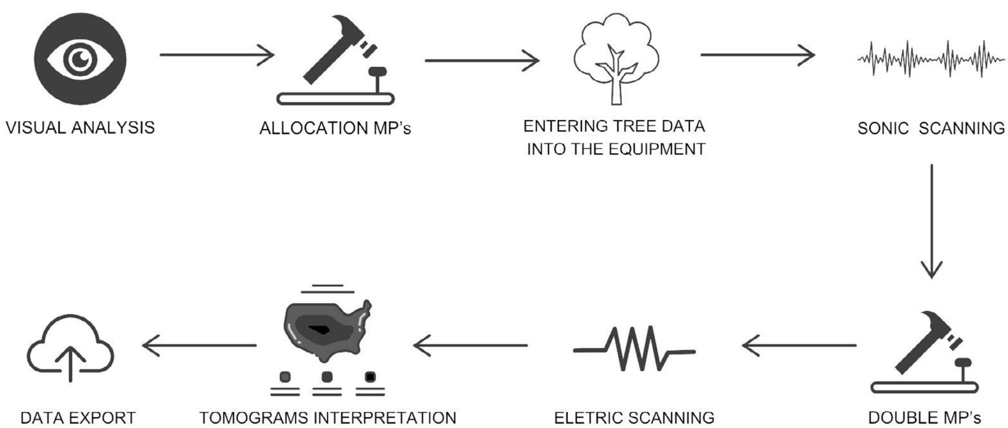

Figure 1: Sequence of activities for internal analysis of the trunk via tomograms.

RESULTS

Sonic tomography (SoT)

Sonic tomography was performed on *Spathodea campanulata* trees with varying health conditions. The analysis revealed that 27.9% of the trees exhibited significant internal decay, including cavities, cracks, and structural deterioration. These defects, which weaken the mechanical integrity of the trunk, were identified through variations in sound wave propagation. Figure 2 presents the tomographic measurements of trunk sections, highlighting the internal defects detected in the analyzed trees.

Figure 3 shows the measurements of sections of *Spathodea campanulata* individuals exhibiting internal trunk defects in lesser proportions as determined by SoT. These trees that presented areas with potential defects; nonetheless, these areas represent a smaller proportion of the trunk area. This result emphasizes the necessity for monitoring these individuals as they are in the early stages of the decay process (Figure 3).

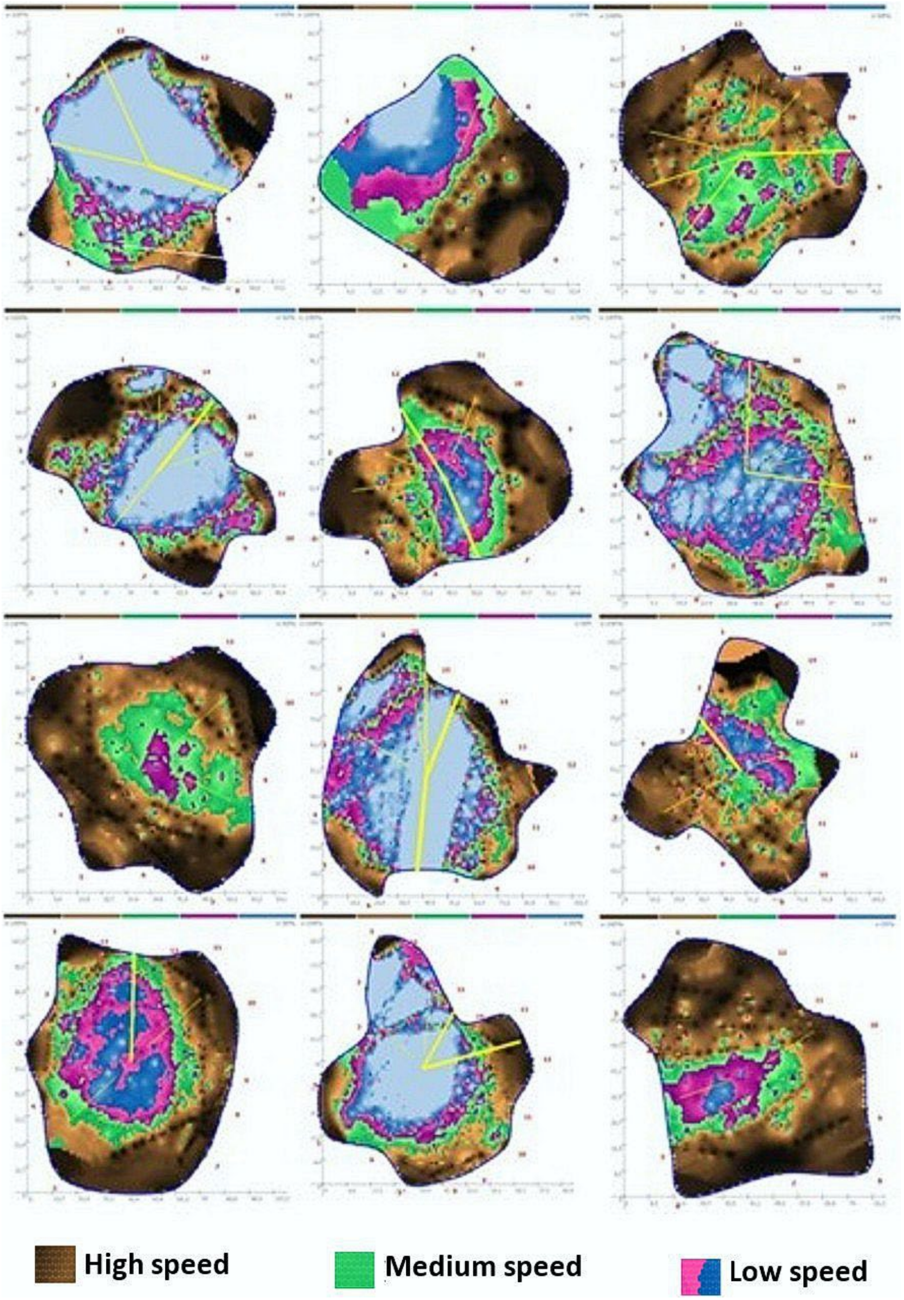

Figure 2: Measurements of the trunk sections of *Spathodea campanulata* individuals exhibiting prominent internal condition defects using sonic tomography (SoT).

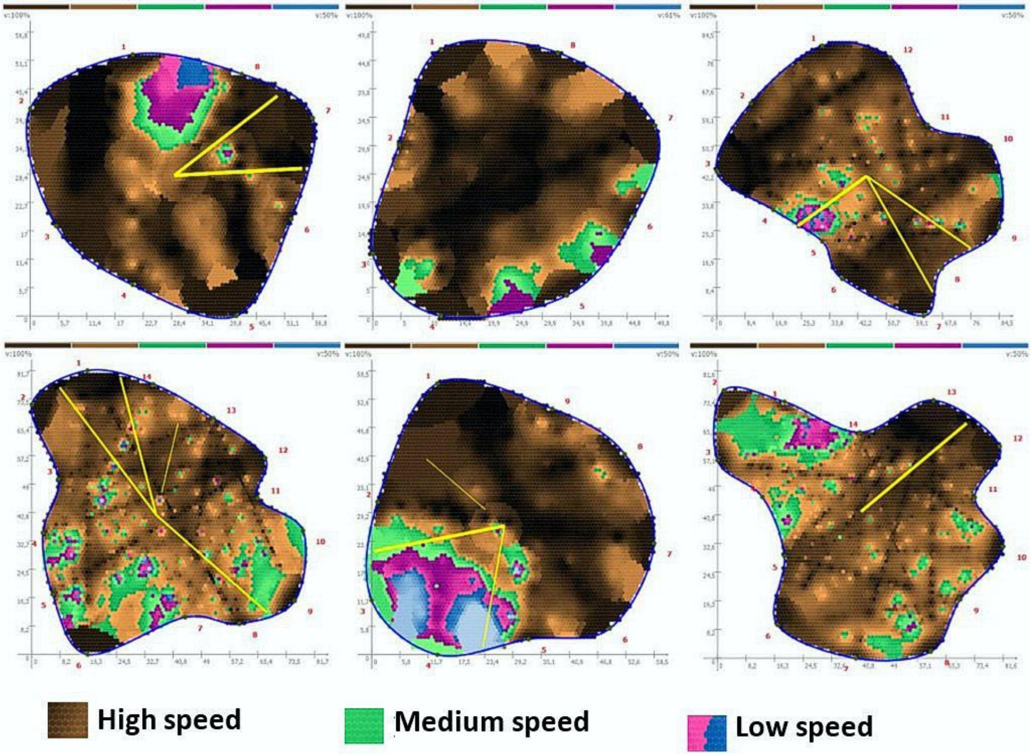

Figure 3: Measurements of sections of *Spathodea campanulata* individuals exhibiting internal trunk defects in lesser proportions as determined by sonic tomography (SoT).

Electrical Resistance Tomography (ERT)

Electrical Resistance Tomography was also applied to *Spathodea campanulata* trees with varying health conditions to assess their structural integrity and detect signs of decay. For the analysis of electrical resistance tomography, it is necessary to understand the pattern of the species to avoid interpretation errors, since resistivity patterns may be related to the relative humidity of the wood (Divakara and Chaithra, 2022). Secondly, it is necessary to disregard trees with medium and high velocity values on sonic tomography – which suggests a possible decline in wood quality. Afterwards, it was found that 80% of the trees exhibited low electrical conductivity in the central region of the trunk. In other words, the healthy trees showed high resistance in the center (red) and low resistance at the edges, with higher moisture content at the ends than in the central portion, indicating that the heartwood of Spathodea campanulata has lower conductivity (higher resistivity) than the end of the tree.

Figure 4 illustrates *Spathodea campanulata* trees exhibiting internal deterioration in the central trunk section, as detected through Electrical Resistance Tomography (ERT). The analysis revealed that 18.6% of the evaluated trees displayed an atypical resistivity pattern, with lower resistivity in the center compared to the ends. This finding suggests increased moisture content in the central portion, indicative of internal trunk decay.

Figure 5 presents trees with areas of reduced electrical conductivity, as detected through ERT. Notably, 13.9% of the analyses did not clearly define the tree's condition, highlighting the limitations of ERT in certain cases.

Figure 6 displays individuals with low electrical conductivity regions, where cavities had been previously identified using ERT. The presence of cavities leads to areas of high resistivity (red), which can sometimes result in misinterpretations. This effect was observed in 9.3% of the trees after field verification and a thorough review of the ERT manual.

Combined Analysis (SoT + ERT)

The combined analysis of the tomographies reveals that 30.3% of the individuals exhibit cavities or significant internal trunk decay (Figure 7). Based on this analysis, it can be stated that 53.5% of the trees exhibited solid wood, eliminating any potential issues with the internal condition of the tree.

The correlation analysis performed between the results obtained from the sonic tomography and the electrical resistance tomography produced a coefficient of 0.72, indicating a strong similarity between their respective results of the internal wood condition.

When comparing the individual usage of each device to their combined usage, a stronger correlation was observed for the sonic tomography (0.91) compared to the electrical resistance tomography (0.86). Thus, the sonic tomography demonstrated greater accuracy when compared to the electrical resistance tomography.

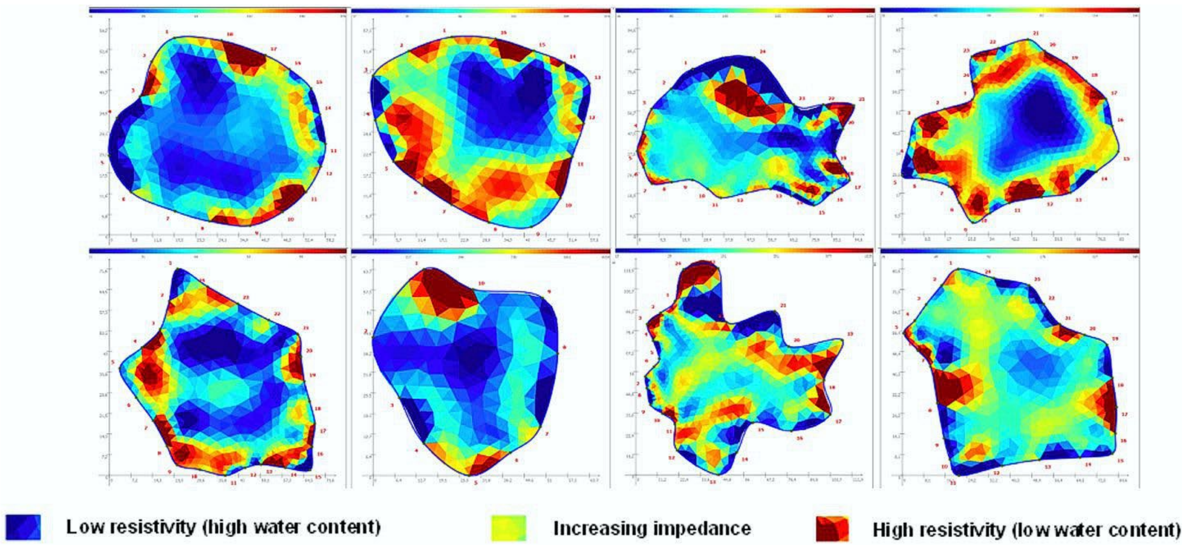

Figure 4: Individuals of *Spathodea campanulata* exhibiting internal deterioration in the central trunk section, as observed through Electrical Resistance Tomography (ERT).

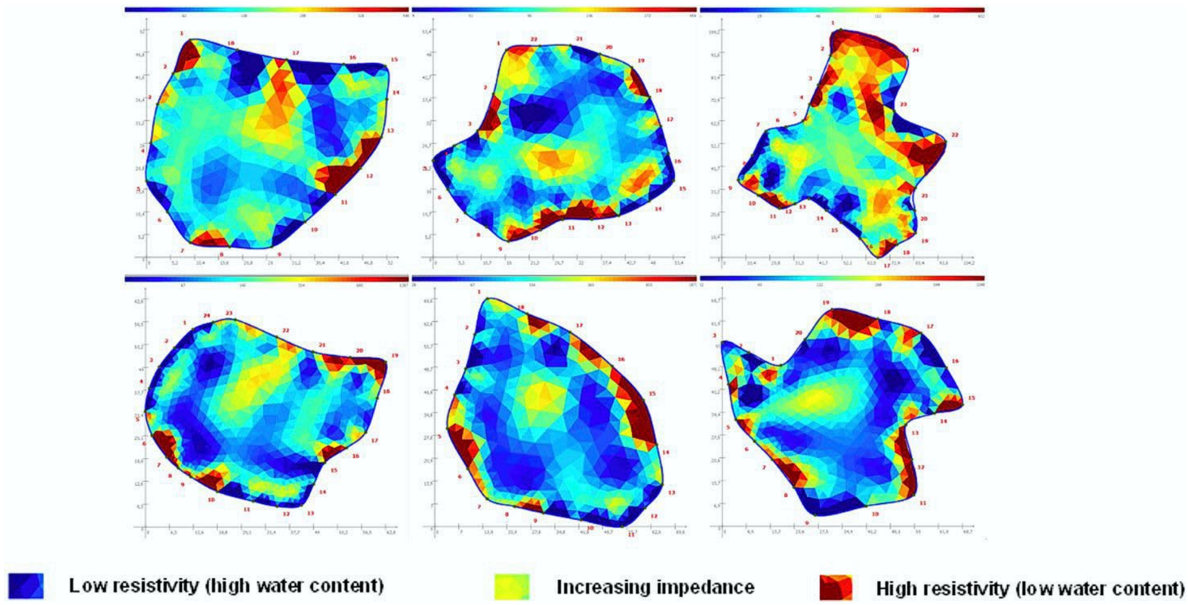

Figure 5: Individuals with areas of diminished electrical conductivity, as indicated by the electrical resistance tomography (ERT).

Regardless, using sonic and electrical resistance information enables a more comprehensive analysis of a tree, allowing for a more precise diagnosis of the nature of defect (such as crack, cavity, or decay) (Göcke, 2017), which better supports decision-making processes in urban forest management.

DISCUSSION

Influence of Wood Decay on the Sonic tomography images

Changes in colors in Figure 2 represent variations in sound wave propagation velocity within the analyzed wood section. Dark brown indicates areas with high-speed waves, while blue/pink represents an area with lower conductivity waves, reflecting a poor relationship between elasticity/density modules, which occurs due to the degradation of a significant amount of wood cellulose, hemicellulose, and lignin through wood decay. It leads to a decrease in density due to the formation of defects inside the trunk. Whereas sound needs a physical medium to propagate, the change in density alters the sound wave propagation time as its path changes from a straight line to a curved line (Yue et al., 2019).

Images with high levels of light blue (Figure 2) can also indicate the presence of internal cracks since their presence compromises the linearity of the wave's path, diverting it to a longer path than the natural one (Wang and Allison, 2008).

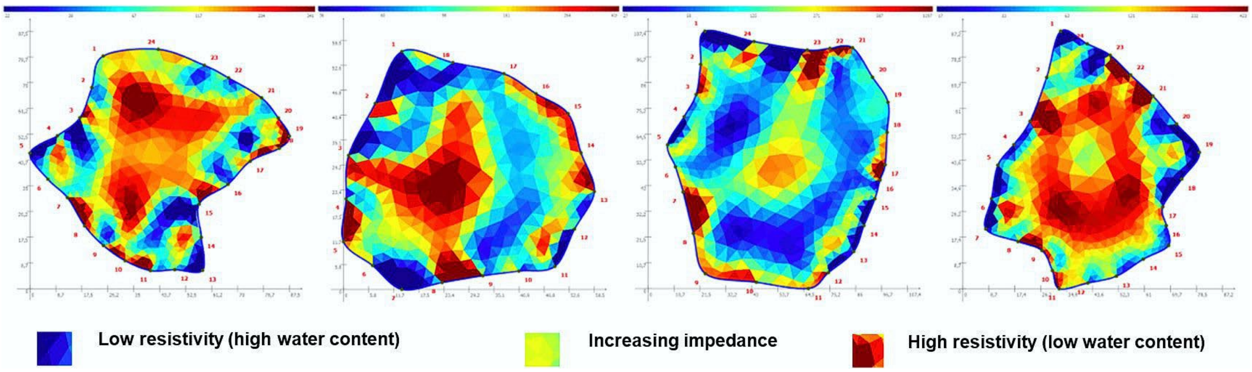

Figure 6: Individuals with low electrical conductivity regions with a previously identified presence of cavities based on Electrical Resistance Tomography (ERT).

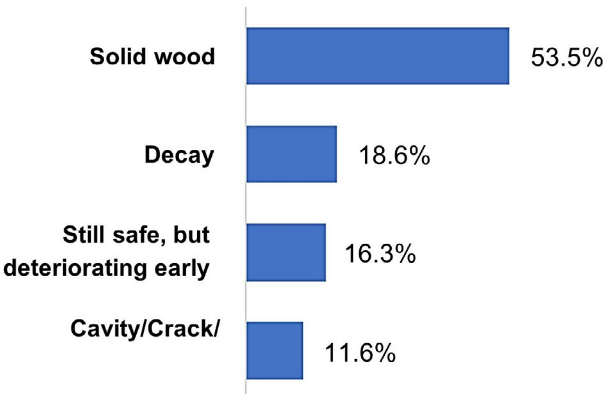

Figure 7: Characterization of the internal trunk condition for the *Spathodea campanulata* individuals evaluated by the two types of tomographies.

This group, where light blue spots appear, primarily included trees that exhibited high and medium velocity values in their central section of the trunk, as well as those with high and medium velocity values at the ends, covering more than 50% of the area. It is important to emphasize that when trunk decay occurs at one of the ends rather than in the center, the resistance moment (the tree's capacity to withstand external mechanical loads) in the opposite direction to the decay decreases to a greater degree because the tensile force in the wood is greater than the compressive force (Rinn, 2014). Thus, the loss of strength in a cross-sectional area of a trunk depends not only on the extent of degradation but also, primarily, on its location.

It should be taken into account that the size of the defect that the equipment can detect depends on the tree diameter, the number of allocated measurement points, and the wood type (the denser the wood, the smaller the detectable defect). In general, the smallest detectable anomaly is in the range of 5 to 10 cm, which eliminates certain assumptions such as drill holes (Gilbert and Smiley, 2004).

This allows for monitoring based on the progression or non-progression of the anomaly, considering that the initiation of wood decay in live trees starts with the presence of any kind of wound (Shortle and Dudzik, 2012).

However, knowledge about how to detect decay in its early stage on stem wood is still very limited and requires further studies (Deflorio et al., 2007), since the speed of the sound wave can be influenced by the components of the wood, which vary with the species (Deflorio et al., 2008).

Among the analyzed trees (Figure 3), a significant proportion (58.1%) displayed uniform sound propagation velocity, resulting in a tomography with predominantly light and dark brown color. However, it should be noted that this finding does not necessarily imply high wood resistance, but rather indicates the absence of changes in sound wave propagation.

Dudkiewicz and Durlak (2023) mention that, in some cases, the trajectory of sound waves can be influenced by the internal structure of wood, such as the existence of reaction wood, for example, leading to results that must be validated with other methods.

It is important to interpret this type of result attentively, as illustrated by studies conducted by Deflorio et al. (2007), in which the sonic tomography did not detect cases of deterioration advancing from the periphery to the center, potentially influenced by the invasive profile of the decomposing fungus. Considering that the wind can introduce bending stresses in that direction (Mattheck and Breloer, 2003). Caution is important when interpreting the result.

Moreover, both the mathematical equation employed by the manufacturer's software and the frequency of impact measurements are relevant features that contribute to the resolution quality of the tomographies. Calculations based on the isotropic properties of wood, for instance, give rise to the so-called "ghost effect," which either overestimates or underestimates the wave velocity (Nicolotti et al., 2003). Although not clearly elucidated by the equipment manufacturer, this factor is likely associated with the complexity of the cross-sectional shape.

Although several researchers have suggested new algorithms that take into account wood anisotropy (Maurer et al. 2006; Liu and Li 2018; Espinosa et al. 2020), the methods are not available for practical use in the market, and further studies focusing on points of improvement are needed (Burcham et al., 2023).

In other words, the closer the stem resembles a circle, the greater the accuracy of the equipament, and vice versa (Rabe et al., 2012). In addition, sonic CT scanners can also be misinterpreted in relation to cracks, including peels and some types of deterioration. Such anomalies can alter the speed of sound waves unexpectedly (Melson and Council, 2023).

This difficulty can be overcome by integrating other wood decay assessment methods, including visual evaluations, tomographies utilizing alternative operating principles, or resistograph.

Electrical Resistance Tomography Patterns in Decayed Wood

The analysis of electrical resistance tomography reveals that 18.6% of the evaluated *Spathodea campanulata* individuals presented a condition contrary to the species pattern, with lower resistivity in the center than at the ends (Figure 4). This occurs because once the wood degradation process begins, its cell walls decompose, leading to wood rot and disintegration. When the wood is decayed and discolored, the growth of fungal hyphae necessitates abundant water, increasing the moisture content in the deteriorated area. Consequently, there is an elevation in the concentration of metallic ions such as potassium, calcium, manganese, and magnesium in the wood, compromising its resistivity compared to healthy wood (Yue et al., 2019). Furthermore, resistivity is influenced by the porosity and texture of the wood, which are also altered during the decomposition process (Nicolotti et al., 2003).

Figure 5 shows the analyses using electrical tomography did not clearly provide the conditions of some trees. In these analyses, the central portion of the trees exhibited intermediate resistivity (green/yellow), making it impossible to classify the central portion as either high (red) or low resistivity (blue).

Furthermore, in the last three trees, although the species pattern can be subtly perceived, the proportion of the trunk with low resistivity values (greater blue area) predominated in the image.

In this case, the result would need to be confirmed through other methods, using, for example, resistograph. Future studies can, however, be dedicated to understanding the ranges of electrical resistivity values common for healthy wood and with anomalies, despite the challenge in establishing such classes for different species.

The user manual of the tomography states that assessing the health and stability of trees based on electrical resistance requires extensive expertise once the electrical resistance of wood is influenced by various factors, primarily: water content; chemical elements that vary with the state of the wood; and cellular structure (such as reaction wood) (Gocke, 2017). In this regard, it is important to consider the possibility of the absence of wood in the center of a tree, indicating the presence of cavities.

The existence of cavities was already known before conducting the tomography scan. Some of them served as nests for bees, with external openings that could be easily recognized because of the intense presence of insects (Figure 6).

In conclusion, the electrical resistance tomography identified problems in 25.6% of the trees. Out of the 11 trees examined, 8 were diagnosed with a significant deterioration of the wood condition also confirmed using the sonic also confirmed by the use of the sonic tomography.

Main differences between SoT and ERT

Three trees had problems with the electrical resistance tomography - but not with the sonic tomography. Among them, only one demonstrated homogeneous sound propagation velocity and had lower electrical resistivity in its central region. These findings indicate the possibility of different interpretations between the equipment used.

It is well-known that during early decay stages, the electrical resistance tomography is more accurate compared to the sonic tomography. This is attributed to the presence of decomposing fungi between the wood cells, which secrete enzymes to break down cellulose, hemicellulose, and lignin, leading to chemical composition, thereby altering the chemical composition of the wood in the initial colonization stages, which influences the resistivity. On the other hand, the sonic tomography depends on the presence of spaces that can significantly modify the sound wave path (Yue et al., 2019). It has better performance when there is pronounced degradation in cavities and fissures.

The manufacturer's manual also points out that resistivity tests are often used as a prediction, as degradation can be detected in extremely early stages - incapable of affecting the modulus of elasticity (MOE), which, along with density, determines the speed of the sound wave. Prior visual inspection can guide the interpretation process (Gocke, 2017).

One of the individuals had a small portion of the trunk with medium and high sound propagation velocities (blue-pink-green) and was classified in two different ways: (1) by the sonic tomography: intermediate group of internal wood decay and (2) by the electrical resistance tomography: lower electrical resistivity in the central portion (blue) – considered the main group.

ERT identified only one individual in the group "indeterminate condition". The sonic tomography may have underestimated the extent of degradation, as similar to findings reported by Burcham et al. (2019), where the equipment showed reduced sensitivity in detecting minor alterations in sound wave propagation. This limitation should be considered when interpreting the results.

On the other hand, variations between the sapwood and heartwood can induce differences conclusions in wood resistivity and lead to false conclusions regarding deterioration when using electrical resistance tomographies (Bieker and Rust, 2010), as chemical and physical changes occur in the xylem tissues as they lose their function. Additionally, highly conductive areas can mask regions of low conductivity where cavities are located, influencing the interpretation of readings by the software (Brazee et al., 2011).

CONCLUSIONS

After analyzing readings from different tomographies for *Spathodea campanulata* individuals, two different results were found when measuring internal wood decay of the trunk: 25.6% through the sonic tomography and 30.2% through the electrical resistance tomography (ERT). Through the combined utilization of both equipment, the following results were observed: 53.5% of the trees had good internal trunk condition, 18.6% had significant internal decay, 16.3% showed an early stage of deterioration, and 11.6% showed an advanced state of wood deterioration with cavities inside the trunk. Among the studied individuals, five showed results that were interpreted differently by the devices. The correlation between the results of the two pieces of equipment was 0.72, signifying a strong association between them. Consequently, both tomographies provided valuable information to assist in diagnosing the internal trunk condition, but when used together, the information can be more easily interpreted. In this sense, future studies should focus on understanding the aspects that lead to different results for the same individuals evaluated by the CT scanners, to avoid misinterpretations about the internal condition of the tree trunk. The result of the study shows that the association of equipment is always the best way for this type of evaluation, corroborating the manufacturer's recommendation. Other methods should be associated with these analyses to increase the accuracy of the results, such as penetrograph and rubber hammer, for example.

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AUTHORSHIP CONTRIBUTION

Project Idea: T. E.; A. M.

Funding: A. M.; M. M. S.

Database: T. E.; A. M.; M. M. S.

Processing: T. E.; A. M.

Analysis: T. E.; A. M.

Writing: T. E.; A. M.

Review: T. E.; A. M.

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