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Comparative evaluation of inspection techniques for decay detection in urban trees

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Abstract: A crucial problem associated with urban trees is the need ensure citizens' safety. It requires the development and application of rapid and precise diagnostic techniques for detecting decay and other types of structural defects in trees to prevent falling due to strength failure or damage caused by internal decay. Significant effort has been devoted to developing robust non-destructive technologies, such as specialized sensors, capable of predicting the intrinsic properties of the wood of individual trees. In this study, the authors used four different devices with its sensors to measure decay: a microsecond timer, an electric resistivity tomograph, an acoustic tomograph and a resistograph. An inspection protocol combined stress wave, electrical resistance, and drilling resistance to detect internal defects on Mindi trees (*Melia azedarach* L.) located in the city of Reggio Calabria in Southern Italy. The percentages of the decayed wood areas, calculated by the different instruments, were compared to establish at which degree the use of simple and rapid instruments can guarantee reliability in detecting the extent of damaged woody tissues. This study's experimental results indicate high correlations between the resistance drilling and the stress wave methods. These high correlations may provide the opportunity to replace the resistograph with the microsecond timer or the acoustic tomograph, both of which are less invasive tools for detecting defects in standing trees. Compared to the resistograph, the electrical resistivity tomograph proved to be the least sensitive instrument for detecting wood decay.

Keywords: Different sensors; Deteriorated wood; Drilling resistance; Stress wave; Tomography; physical signals.

1. Introduction

Green areas in cities are acquiring an increasingly important role in urban architecture. Within urban communities, trees are valuable assets that provide ecological, aesthetic, social, and economic benefits. In fact, urban trees play a significant role in our daily life and are valuable assets to communities and a healthy environment [1]. However, at the same time, they pose a potential risk to people and property when they become structurally unstable [2]. A crucial problem associated with urban trees is the need to know and evaluate their health to ensure citizens' safety and security. The internal defect in tree stem or branch weakens the health of forest, declines the quality and value of timber, and poses a risk of public safety in urban communities [3]. In recent years, trees' potential to cause harm has been increasing because of climate change effects, mainly related to windstorms and tree diseases that cause trees to fall [4,5]. Accidents related to trees' and branches' sudden falls keep administrations' and individuals' attention on the problem of tree safety. For this reason, public and private owners are called to quantify and monitor their trees' risk to public safety [5]. Consequently, the detection, evaluation, and management of hazardous trees has become a major concern for urban foresters and park managers [6]. For this reason, the theories and application protocols for evaluating trees' stability are the subject of a wide debate involving researchers and technicians. A thorough inspection of trees' branches, stems and root collars is essential in detecting hazardous conditions [6]. Tree risk assessment is a methodical process for identifying, analysing and evaluating risk [7,8], and the Visual Tree Assessment method [9] represents an internationally recognized procedure for tree health assessment. Arboriculturists consider visual tree assessment an essential practice that serves as the starting point for evaluating tree defects and providing basic information regarding tree growth performance and stability [10]. The method involves four phases: (*i)* visual inspection; (*ii*) any instrumental investigation that highlights the presence of structural defects; (*iii*) assignment of the subsidence propensity class or phytostatic risk categories and (*iv*) definition of operational note to restore the tree's static balance or, in extreme cases, to recommend its felling. Visual inspection is aimed at identifying all visible components of a tree and any symptoms indicative of structural defects that could compromise its stability. The instrumental investigation quantitatively describes any anomalies found. This kind of analysis can make use of the different available investigation methods: identification of discontinuities in tissues by means of sonic or ultrasonic systems, measurement of wood density with penetrometric systems, evaluation of the wood's mechanical characteristics with destructive tests, electrical resistivity, radar and other techniques [11-17]. Concerns related to public safety support the development and application of rapid and precise diagnostic technologies to detect decay and other types of structural defects in trees [2]. Destructive testing destroys or changes the part examined, while non-destructive methods, do not leave any permanent traces. Among the second group can be found methods based on the propagation of electromagnetic waves including ultrasound methods [18, 19]. Between the two categories, there is the semi-desctrucitive methods category in which tests are characterized by a low impact on the object. In this group, among others, fall penetration methods, leaving traces in the form of holes with a small diameter (hardness tests, resistance drilling tests) [20, 21]. Significant effort has been devoted to developing robust non-destructive technologies that are capable of predicting individual trees' intrinsic wood properties [22]. The assessment of wood via stress waves is one of the oldest and simplest methods available [23]. A typical approach for measuring wave propagation velocity in standing trees involves inserting two sensor probes (a transmit probe and a receiver probe) into the sapwood and introducing stress wave energy into the tree trunk from a point source through a hammer impact [24,25]. This procedure is referred to as a single-path stress wave timing measurement, and the stress wave velocity obtained is related to the physical condition of the tree. The single-path method is fast, economical, and easy. Acoustic methods have been found to be very effective for detecting the internal decay of urban trees [26]. The concept of detecting decay using ultrasound or sound waves is based on the observation that stress wave propagation is sensitive to the presence of degradation in wood [27]. In general, stress waves travel faster in high-quality wood than in deteriorated and low-quality wood [28,29]. The health of a tree can be assessed also by means of penetrometers and drilling resistance tools. Resistance drilling measures the relative resistance (drilling torque) of the material as a rotating needle is driven into the wood at a constant speed and changes in wood resistance are displayed on a graph as changes in mechanical resistance. Areas of prolonged low resistance indicate decay, cavities, or cracks [27]. Furthermore, drilling does not require the removal of the bark, and the width of the hole in the tree is barely visible making it the least harmful invasive method.

Many authors have already worked on detecting wood anomalies in trunks or standing trees, applying in most cases a single method and in fewer cases using and comparing two or more techniques with the aim of defining a fast method to identify potential risk in urban forests. Nicolotti et al. [30] reported application of electric, ultrasonic and georadar tomography for detection of tree decay and the comparison of these methods with the traditional penetrometer in an urban environment. Brazee et al. [31] studied the determination of internal decay comparing acoustic and electrical impedance tomography. Wang et al. [29] and Rinn [32], for similar studies, used acoustic tomography subsequently verified by resistograph testing. Qin et al. [33] conducted health assessment of *Cinnamomum camphora* tree logs by combining the acoustic-laser technique and acoustic tomography. The acoustic-laser technique uses the acoustic excitation generated by a loudspeaker designed to vibrate the object with frequencies up to 20,000 Hz, and a laser beam to measure the vibrational frequency response. The difference in the response signal can identify whether the localized region is intact or defective. Their results demonstrated that the acoustic-laser technique could identify the presence of near-surface trunk defects that are normally overlooked by the conventional acoustic tomography measurements with random sensor distribution. Lin et al. [34] detected deterioration in royal palm combining the use of ultrasonic tomographic and resistance drilling techniques and found a high correlation between the amount of decay detected by ultrasonic tomography and the amount actually present in cross-sections of discs and living palms according to the drill-resistance profile. Several years later, two of the authors [11] from that study compared acoustic velocity and electrical resistance tomography for evaluation of peripheral-inner wood demarcation in urban royal palms, suggesting combining these methods with drilling resistance profiling.

This study’s aim was to determine the precision of four different methods in detecting and quantifying decay in Mindi trees (*Melia azedarach* L.) in an urban context in the metropolitan city of Reggio Calabria (Italy). In particular, the research was aimed at (*i*) calculating the amount of deteriorated wood with a microsecond timer, acoustic tomography, electric resistivity tomography and resistograph and (*ii*) verifying, by comparing the resistographic results with the results obtained by all three instruments, the results' reliability in determining the amount of deteriorated woody tissues.

2. Materials and Methods

2.1. Study area and test devices used

The tests were conducted on 75 mindi trees (*Melia azedarach* L., Meliaceae) located along the edges of some streets in the metropolitan city of Reggio Calabria (Italy; Fig. 1). Mindi trees, in Italy, is one of the most widespread species used in urban architecture; in fact, it is often planted in parks, gardens and alongside paths as an ornamental tree. Table 1 describes some physical characteristics of the Mindi wood measured at the wood technology laboratory. The media and the standard deviation (SD) values confirm what has been reported in various studies regarding wood density and shrinkage [35]. It is a small to medium size, deciduous tree characterised by a large trunk and many branches. In this study, various measurement methods were applied to detect internal defects in standing trees and four devices were used: a Fakopp microsecond timer (Fakopp Enterprise, Agfalva, Hungary), an ArborSonic 3D acoustic tomograph (Fakopp Enterprise Ltd., Hungary), a PiCUS TreeTronic (Argus Electronic Gmbh, Rostock, Germany) and an IML-Resi PD400 Resistograph (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany). As reported by Proto et al. [22], the samples trees were monitored at a height of approximately 50 cm above the ground.

Fig.1. The location of a first sample of 23 trees monitored in the municipality of Reggio Calabria.

Table 1. Physical properties of *Melia azedaracht* trees

2.2. Microsecond timer

To investigate if inside the trees there were wood defects, after a preliminary visual inspection, the microsecond timer device (Fakopp Bt. Agfalva, Hungary) was used to generate single-path stress waves on the trees. This tool consists of needles attached to accelerometers, used as mediators, that penetrate the bark and reach a tree's sapwood. A hammer is used to tap the start sensor to generate a stress wave in the tree stem in the radial direction. The two sensors transmit with a frequency of about 23 kHz and pick up the start and stop signals, and the wave transmission time is displayed on an LCD screen with a 1-µs resolution. Following the instructions dictated by the instrument's manufacturer, the trunks were tested by aligning the two probes on the trunk in a north-south (NS) level position for the first test and in a west-east (WE) level position for the second test. The tests were repeated several times for each pair of sensors to derive average values from at least three readings. Through the sound wave’s speed, it is possible to immediately establish whether there is a cavity or degraded wood in the area between the two sensors. The principle on which the analysis is based is simple: if there is a cavity or decayed wood, the sound waves produced by the hammer’s impact do not propagate along the straight line joining the sensors, but rather go around the cavity remaining in the sound wood. Accordingly, the waves take more time to reach the sensor block in the presence of decay [36-38].

2.3. Acoustic tomograph

The same 75 trees were non-destructively tested using the ArborSonic 3D acoustic tomograph device (Fakopp Bt. Agfalva, Hungary). The tests were performed in accordance with the manufacturer’s and software’s instructions, and these test procedures are explained in many similar papers [39-42]. Eight high sensitivity SD02 piezo-sensors with measurement error of ± 3 microseconds were used on each standing tree one placed at each of the eight different cardinal and intercardinal points. The travel times (in μs) generated by each sensor were captured by the other sensors, thus determining the acoustic velocity. Every measurement was repeated three times (repetitions) on each sensor to obtain averaged travel times, thus reducing uncertainty related to individual tests.

2.4. Electrical resistivity tomography

The electrical resistivity tomography (ERT) was used to measure the electrical resistivity (reciprocal to electrical conductivity) for the same 75 trees. The measurement was conducted with the Picus Treetronic device (Argus electronic GmbH, Rostock, Germany). The test applied eight electrodes, evenly placed around the trunk in a horizontal plane using a dipole–dipole configuration at a low-frequency current of 8.3 Hz. Each electrode was clipped and attached to a nail (with a 2-mm diameter) that had been tightly forced into the bark and sapwood. Upon completion of the electrical resistivity measurements at each level, a tomogram was constructed for the cross-section using Picus Q72 software. The electrical resistance between the sensors is calculated using the voltage and current values and the distance between the sensors [43-45]. The outcome is a tomogram: a two-dimensional image where the distribution of electrical resistance values in the stem cross-section is depicted using a relative colour scale. Red-coloured areas represent the areas with relatively increased resistance, whereas blue-coloured areas represent areas with relatively decreased resistance. The image consists of a grid of tessellating triangles, with each triangle having its own electrical resistance reading.

2.5. Resistograph

The drilling resistance test was conducted using an IML-Resi PD400 (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) resistograph equipped with a 400-mm-long and 3-mm-thick steel drill (tip diameter 3 mm, shaft diameter 1.5 mm). A drilling resistance tool consists of a power drill unit, a small-diameter spade-type drill bit and an electronic device that can be connected to the serial interface input of any standard personal computer. The method is based on measuring the drilling resistance along a small needle path when a needle is driven into a tree with a constant force [46]. This system produces a chart showing the relative resistance over the needle's travel path. Areas of sound wood have varying levels of resistance, whereas voids and areas of decay show no resistance, so the user can determine areas of low, mild and high decay levels [47]. During the drilling measurement process, the relative drilling resistance, feeding force and speed parameters can be continuously measured as a function of the drill bit's position along the drilling path [48]. Measurements were performed at the height of the trees of approximately 50 cm above the ground. The perforation was set at 2 cm m^{-1} forward speed (feed speed) with a rotation rate of 3500 rpm along the radial direction of the trees' stems, producing a trace chart at a 0.1-mm sampling interval. Like the microsecond timer tests, the drilling resistance tests were conducted drilling the trunk in a NS level position for the first test and in a WE level position for the second test. The test results were transmitted to a computer and processed with dedicated software (Fig. 2).

Fig. 2. Drilling resistance record measured on trees belonging to different classes of damaged wood.

2.6. Data processing and Statistical analysis

Following all the measurements with the different tools, the study proceeded to assess the percentage of the degraded wood area in correspondence with the inspected section. During the microsecond timer tests, the velocities of single-path stress waves (VW) were obtained in a north-south level position (VW-NS) and a west-east level position (VW-WE). The distance between the two sensors, determined by a tape measure, was used to calculate the propagation speed (in m/s) of the stress wave into the wood between the two sensors. The percentage of wood deterioration detected by the microsecond timer (DZ_{VW}) was obtained from the ratio between the reference value [49] of the velocity of the stress waves V_0 (the average value found in the healthy wood) and the value of the stress waves measured for each deteriorated tree (V_d) following Equation 1:

$$DZ_{\mathrm{VW}} = \frac{V_0 - V_d}{V_0} \times 100\ [\%] \qquad \text{(Eq. 1)}$$

As explained below in the dedicated drilling test presentation, since the study's purpose was to compare the results obtained from all the instruments used for decay detection with the resistographic results, of all the paths recorded by both electrical and acoustic tomography, only the paths between sensors 1-5 and 3-7 were considered in the study. These paths in the trunks coincided with the NS and WE positions (i.e. the same paths monitored with the resistograph and microsecond timer tools). For the tomographic data (acoustic and electrical), the percentage of the decayed wood area was obtained with the same approach used for the microsecond timer. Particularly, concerning the acoustic tomography, because the ArborSonic 3D software provides the velocities of the path of the acoustic wave between sensors, the percentage of the decayed wood areas was calculated with the Equation 2:

$$DZ_{TS} = \frac{V_{a0} - V_{ad}}{V_{a0}} \times 100\ [\%] \qquad \text{(Eq. 2)}$$

where DZ_{TS} is the extent of decayed wood as a percentage of the total trunk area surveyed by acoustic tomograph, V_{a0} is the average value of the velocities of the acoustic waves found in the healthy wood and V_{ad} is the velocity of the acoustic waves found in the sensing direction in the decayed section.

Regarding electrical resistivity tomography, several studies have used image analysis to interpret tomographic results [31, 5051]. However, due to the relativity of the colour scale for each tomogram, this study has focused on the values of electrical resistivity of each triangle in order to accurately calculate the image resistance values of the resistance tomography. To achieve this, the colour image was first converted to grayscale and then the pixel values in the graph were converted to resistance values using the MATLAB software (MathWorks, Natick, MA, USA) [52,53], ultimately creating a grid of electrical resistivity values (Fig. 3). In this study, only the electrical resistances values found in the pixels of the NW and WE positions of the tomogram were considered, so that they could be compared with the other instruments' results. The severity of decay detected with the electrical resistivity tomograph was calculated following Equation 3:

$$DZ_{E} = \frac{R_0 - R_d}{R_0} \times 100\ [\%] \qquad \text{(Eq. 3)}$$

where DZ_E is the extent of decayed wood as a percentage of the total trunk area surveyed by electrical resistivity tomograph, R_0 is the average value of the healthy wood's electrical resistivity and R_d is the average electrical resistivity value in the sensing direction in the decayed section.

Fig. 3. An original electrical tomogram (A) and a corresponding electrical resistivity grid (B).

For the drilling tests, the software used for resistograph analysis was PD-tools Pro V. 1.22. Similar to Reinprecht and Šupina's [49] approach, the extent of damaged zone determined by resistograph (DZ_R) was computed in a percentage using Equation 4:

$$DZ_R = \frac{d_R}{\mathrm{L}} \times 100\ [\%] \qquad \text{(Eq. 4)}$$

where L is the diameter of the tree, and d_R is the total length (mm) of the tree's significantly damaged zones. The distinction into various damage classes was achieved using a threshold of about 33% of wood deterioration [54], considering the percentage of decayed wood recorded by the two paths of the resistograph. The damaged zones along the radial direction of trees were obtained in a NS level position (DZ_R-NS) and in a west-east level position (DZ_R-WE). Since the resistograph provides accurate data through a mechanical measurement given by the resistance of the woody tissues against the drilling, the data are recorded in the characteristic form of a graph, which can describe the trunk's internal conditions. In fact, following the same theory of Johnstone et al. [55], wood decay was believed to occur when there was significant "yield" on the graph in relation to the rest of the trace and a lack of "peaks" on the graph associated with growth increments, without reference to the cut stem. This tool's results have therefore been taken as a reference for comparison with other tools that provide inaccurate path data through techniques that exploit wood's ability to transmit acoustic, electrical, and stress waves. Table 2 shows the abbreviation codes used to describe the damaged zones detected by the different tools used in this research.

Table 2. List of acronyms used to describe the detected damaged zones.

SPSS software version 20.0 (IBM Corp., Amonk, NY, USA) was used for statistical data analysis. To determine the differences in the decay detection results among the applied techniques compared to the resistograph measurements, the authors evaluated the relationships between the percentage of the damaged zones of trees (DZ) determined by resistograph (DZ_R) and those reported by the other tools (DZ_{VW}, DZ_{TS} and DZ_E for damaged zones detected with microsecond timer, acoustic tomography and electric resistivity tomography, respectively) using linear correlations [49].

3. Results

The basic descriptive statistics of the results regarding the percentage of degraded areas obtained by all the tools used in this research are shown in Table 3. The data demonstrate the diversity among the values found with the drilling tests and the other instruments. According to the percentage of damage found with the resistograph throughout the investigated section, the trees were catalogued into three different damage categories: slightly, moderately, and highly (Table 4). A fixed threshold value (33%) for the extent of deterioration was defined to classify the defective classes [54].

Table 3. Descriptive statistics of the damaged zone (%) detected by the various tools for the NS and WE paths.

Table 4. Descriptive statistics of the wood categories distinguished by the percentage of decayed wood detected by the resistograph.

Tight relationships were observed between the damage percentage detected by microsecond timer (DZ_{VW}) and the damaged zones inside the trees determined by the resistograph (DZ_R). The linear correlation between DZ_R-NS and DZ_{VW}-

NS provided an R^2 value of 0.918 (Fig. 4) and that in the west-east direction (DZ_R-WE and DZ_{VW}-WE) obtained a highly similar value: 0.919 (Fig. 5). Similar results were obtained from the correlations between DZ_R-NS and DZ_{TS}-NS and between DZ_R-WE and DZ_{TS}-WE, with R^2 values of 0.875 and 0.882, respectively. A lower correlation was found between DZ_R and DZ_E for both the NS path and the WE path. In fact, between the damaged zones detected by the resistograph and the electrical tomography, there were R^2 values lower than 0.7.

Fig. 6 shows that the difference in decay detection by resistograph compared to the other instruments increased as the extension of the decayed wood increased. Different correlation levels were observed between the percentage of decayed wood detected by the resistograph and those determined by the microsecond timer, the ArborSonic 3D and the TreeTronic for both the NS direction and the WE direction (Table 5).

The observed results for the low-decay wood category showed that the DZ_R and D_Z values detected with the other instruments always showed a significant correlation in both the NS and the WE directions. The microsecond timer and the acoustic tomograph reached the level of 0.01, whereas the correlation was significant at the level of 0.05 for the electrical resistivity. Even in the case of medium-decay wood, the DZ_R and D_Z detected by the microsecond timer (DZ_{VW}) were significantly correlated at 0.01 levels in both directions. On the other hand, for the acoustic tomograph, it was found the correlation of the obtained data was highly significant at 0.01 for the NS path and at 0.05 for the WE path. Regarding the high-decay wood class, there was a decrease in the significance of the correlation between the results obtained with the resistograph and those obtained using the other three instruments. With the exception of the data collected by the acoustic tomograph, which showed a high correlation with the resistograph at only the NS path, the other instruments did not demonstrate any significant correlation.

Fig. 4. The relationships between the percentages of damaged area measured by the resistograph and those measured using the other instruments in the NS direction: (A) resistograph and microsecond timer device, (B) resistograph and acoustic tomography device and (C) resistograph and electrical resistivity tomography device.

Fig. 5. The relationship between the percentages of damaged area measured by the resistograph and the other instruments in the WE direction: (A) resistograph and microsecond timer device, (B) resistograph and acoustic tomography device and (C) resistograph and electrical resistivity tomography device.

Fig. 6. Mean wood decay detected by the different tools on the (A) NS and (B) WE directions.

Table 5. Correlations between the damaged zones detected by the resistograph and those detected by the microsecond timer, acoustic tomography and electrical resistivity tomograph tools in the NS and WE directions.

5. Discussion

Non-destructive testing methods and tools do not always provide extensive information on trees' internal integrity, and this study is focused on determining the precision of four different tools and methods in detecting and quantifying decay in standing trees: microsecond timer, acoustic tomography, electric resistivity tomography and resistograph. All the instruments used in this study demonstrated the ability to effectively detect standing tree trunks' internal decay, but determining the size of damaged zones to identify hazardous trees has been challenging using fast diagnostic techniques. The proposed inspection protocol can support urban tree diagnosis managers in detection, providing highly accurate estimates and tree stability characterisation. In fact, this approach has eliminated the typical inherent limits of each considered tool. Although the resistograph's key features are its modest cost, digital data collection, high-resolution data and ease of field use [56], it has the disadvantage of drilling into the tree, penetrating up to 150 cm. The resulting deep hole in the xylem exposes the tree to fungal spores after measurement [57,30]. Additionally, this method requires considerable time to take each measurement. Using devices with invasive techniques often requires a high level of specialised knowledge and experience [58]. Furthermore, this method provides strictly accurate measurements. Given the strong correlation between their results, the resistograph could be replaced by the microsecond timer, which is a less invasive tool that does not place the tree at risk of biotic attacks, and which guarantees a good detection of anomalies inside the trunks [59]. Regarding the mark left by the measurement, the use of tomographic equipment requires the insertion of standard 5-cm nails through the cortex; these wounds are minor and can heal quickly [31] compared to the deep hole created by the resistograph. It is interesting to note that using the microsecond timer has detected degraded areas even with extensions of less than 0.5% of the wave path in the sensing direction in the surveyed section, whereas the resistograph was less precise. However, the microsecond timer does not allow reconstruction of the entire cross-sectional area. In fact, although it was found to be highly sensitive in detecting wood decay along the single path, the single path stress wave measurement can detect only internal decay that occupies over 20% of the total cross-sectional area [29]. Therefore, several measurements are required to be able to detect defects throughout the study section. The resistograph is portable and easy to handle in the field and in the laboratory, although like the microsecond timer it does not allow reconstruction of the entire cross-sectional area. Additionally, drilling does not require removal of the bark, and the hole in the tree is barely visible. Hence, testing using this tool is considered minimally invasive. However, replacing the resistograph with the microsecond timer would ensure effective preliminary detection of wood decay with even milder wounds on the trunk and very short measurement times due to its easy handling and use. The high correlation demonstrated by this research between the resistograph and the microsecond, at first view, provides the opportunity for preliminary detection of defects in standing trees using only the stress wave method, which is usually cheaper and faster. This association between the two instrumental methods agrees with previous experiments by da Costa et al. [60], who found relationships between the stress wave timer and visual damage analysis in various species' woods.

The sonic tomograph also provided accurate results, albeit slightly less accurate than those of the microsecond timer. As confirmed by other studies, sonic tomography has proven highly effective in detecting the decay of trees' internal tissues

[43,61-65,40-42,1], even in the early stages of wood decomposition [30]. Furthermore, it is a highly accurate non-destructive method in locating anomalies and in estimating their size and shape [22,66]. However, the use of the sonic tomograph, given the greater complexity and duration of its data detection procedure compared to the resistograph and the microsecond timer, is suggested only in case of the need to detect more-detailed data in trees with known internal decay levels and in those that must be monitored over time.

In this study, the electrical resistivity tomograph proved to be the least sensitive instrument for detecting wood decay. Evaluation of the electrical resistivity tomogram can be complicated by each tree species' specific resistance distribution, which may change from season to season [43]. Therefore, electrical resistance tomography requires considerable field practice to correctly interpret image [67,44].

The urban foresters assigned the duty of safety management of these often massive tree structures in close proximity to buildings, roads and people must analyse and apply this new information to their practice [68, 69].

5. Conclusions

Green areas in cities are acquiring an increasingly important role in urban architecture. To the best of the authors' knowledge, this study is the first designed experiment in which a potential inspection protocol in instrumental methodology has been proposed. This approach can be functional to favor the choice and use of one or multiple diagnostic sensors according to the technical-professional needs for a quick and precise evaluation of the failure of the trees. Nevertheless, the visual analysis of an expert technician is preliminarily fundamental [55]. The merit of this study is that it builds up on a reasonably wide dataset collected in the field; seventy-five monitored trees and each with four different NDT tools. Therefore, this research accounts for operational variability, contributing a more precise approach to describing sizes and locations of damaged areas. The study showed that the drilling resistance and single path stress wave equipment identified the different sizes of defects, and being considered rapid tools, they offer a benefit in terms of quality and accuracy of the analyses, even if they are unable to define the entire stem cross-section. However, considering that most arborists apply only the limited visual assessment because tomographic and resistographic tools are considered excessively expensive, the use of an impulse hammer, such as the one used in this study, is much less expensive than the other two methods, and it can provide higher accuracy in detecting decay than the visual method. At the same time, visual assessment remains a fundamental and irreplaceable element in the diagnosis process. Finally, as an attempt at determining the validity of a risk assessment method, this study provides some insights into different methodological approaches' accuracy (stress wave, wood resistance and electrical impedance) as methodical processes for identifying and evaluating tree failure risk that are adopted in different regions of the world. Future research on this topic should aim at a broader assessment of tree risk to better define the accuracy of the entire defect investigation process such as internal wood decay with particular regards to actual damage or injury when the initially used visual technique is insufficient to make management recommendations [8]. Certainly, knowing the level of detail that different sensors can reach in the interception of internal defects of the wood in the trunk of standing trees, will be able to support the decisions of the professionals in choosing the right tool according to their needs and economic capabilities.

CRediT authorship contribution statement

Salvatore F. Papandrea: Methodology, Investigation, Software, Formal analysis & Writing - original draft.

Maria Francesca Cataldo: Software, Formal analysis & Writing - original draft.

Giuseppe Zimbalatti: Supervision.

Andrea R. Proto: Methodology, Investigation, Supervision, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Table 1. Physical properties of *Melia azedaracht* trees

Property	Unit of measure	Mean	SD	N
β_r	%	3.75	2.25	50
β_t	%	6.25	2.15	50
β_a	%	0.38	1.17	50
β_v	%	10.48	3.51	50
ρ_{green}	Kg/m^3	750	2.74	50
ρ_{12}	Kg/m^3	534	1.45	50
ρ_y	Kg/m^3	460	3.96	50

β_r radial shrinkage (%), β_t tangential shrinkage (%), β_a, axial shrinkage (%), β_v volumetric shrinkage (%), ρ_{green} density green wood (kg/m^3), ρ_{12} density at 12% moisture content (kg/m^3), ρ_y basic density (kg/m^3).

Table 2
List of acronyms used to describe the detected damaged zones.

Abbreviation codes	Description
Dzr-NS	Damaged zones along the radial direction of trees, determined by resistograph device on north-south position
Dzvw-NS	Damaged zones along the radial direction of trees, determined by microsecond timer device on north-south position
Dzts-NS	Damaged zones along the radial direction of trees, determined by acoustic tomography device on north-south position
Dze-NS	Damaged zones along the radial direction of trees, determined by electrical resistivity tomography device on north-south position
Dzr-WE	Damaged zones along the radial direction of trees, determined by resistograph device on west-east position
Dzvw-WE	Damaged zones along the radial direction of trees, determined by microsecond timer device on west-east position
Dzts-WE	Damaged zones along the radial direction of trees, determined by acoustic tomography device on west-east position
Dze-WE	Damaged zones along the radial direction of trees, determined by electrical resistivity tomography device on west-east position

Table 3

Descriptive statistics of the damaged zone (%) detected by the various tools for the NS and WE paths.

	N	Minimum	Maximum	Mean	Std. Deviation
Dzr-NS %	75	0.00	75.00	30.61	24.41
Dzr-WE %	75	0.00	74.00	31.57	24.62
Dzvw-NS %	75	0.00	53.89	22.19	17.18
Dzvw-WE %	75	0.00	55.03	22.02	17.41
Dzts-NS %	75	0.00	50.03	19.48	16.61
Dzts-WE %	75	0.00	55.31	20.65	16.59
Dze-NS %	75	0.00	45.00	15.83	13.33
Dze-WE %	75	0.00	52.85	18.64	15.61

Table 4

Descriptive statistics of the wood categories distinguished by the percentage of decayed wood detected by the resistograph.

Wood categories		N	Minimum	Maximum	Mean	Std. Deviation
Sound wood	Dzr-NS %	13	0.00	0.00	0.00	0.00
	Dzr-WE %		0.00	0.00	0.00	0.00
Slightly decayed wood	Dzr-NS %	25	2.00	28.00	14.94	7.54
	Dzr-WE %		2.00	26.66	15.40	7.37
Moderately decayed wood	Dzr-NS %	21	25.00	59.27	41.75	10.56
	Dzr-WE %		30.00	59.00	45.11	10.08
Highly decayed wood	Dzr-NS %	16	60.00	75.00	65.34	4.323
	Dzr-WE %		56.45	74.00	64.73	6.197

Table 5

Correlations between the damaged zones detected by the resistograph and those detected by the microsecond timer, acoustic tomography and electrical resistivity tomograph tools in the NS and WE directions.

			Dzvw-NS %	**Dzts-NS %**	**Dze-NS %**
Slightly decayed wood	**Dzr-NS %**	Correlation	0.669**	0.525**	0.421*
		Sig.	0.000	0.004	0.018
Moderately decayed wood	**Dzr-NS %**	Correlation	0.700**	0.563**	0.127
		Sig.	0.000	0.004	0.292
Highly decayed wood	**Dzr-NS %**	Correlation	0.364	0.643**	-0.054
		Sig.	0.083	0.004	0.422
			Dzvw-WE %	**Dzts-WE %**	**Dze-WE %**
Slightly decayed wood	**Dzr-WE %**	Correlation	0.588**	0.552**	0.360*
		Sig.	0.001	0.002	0.038
Moderately decayed wood	**Dzr-WE %**	Correlation	0.746**	0.466*	-0.064
		Sig.	0.000	0.017	0.392
Highly decayed wood	**Dzr-WE %**	Correlation	0.330	0.419	-0.236
		Sig.	0.106	0.053	0.190

**Correlation is significant at the 0.01 level.

*Correlation is significant at the 0.05 level.