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Review

Structural Stability of Urban Trees Using Visual and Instrumental Techniques: A Review

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Abstract: This review focuses on tree health assessment in urban forest, specifically on the methodologies commonly used to detect levels, dimensions, and location of wood deterioration. The acknowledged benefits to the urban forestry area from the application of assessment techniques are also addressed. A summary is presented of the different methodologies, such as visual analyses, acoustic tomography, and digital wood inspection drill, with the underlined importance of the biodeterioration of wood by fungi and termites.

Keywords: digital wood inspection drill; nondestructive testing; physical and biological investigations; semi-destructive testing; ultrasonic waves

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1. Introduction

Trees are living organisms whose characteristics vary with species, age, climate, and growing conditions; thus, it is difficult to accurately predict when and under what conditions they will fail. Thus, a great deal of effort has been devoted to increasing the precision of the analysis of this complex and important problem [1–3].

The tree physiology and structure play a strong role in shaping the urban tree ecosystem. Urban forests provide critical social and cultural benefits that may strengthen community resilience to climate change. Street trees or urban parks can hold spiritual value, promote social interaction, and contribute to a sense of place and family for residents [4]. Forested urban areas appear to have potentially stronger and more stable communities [5,6].

Studies have found that the extent of urban forest benefits and ecosystem services depends on several factors including tree structure, health condition, and physiology [7–11], as well as the human population density and the character of the environment, whereby it is important to analyze whether the environment has isolated tree pockets or contiguous tree lined corridors [12]. Natural environmental conditions are also important, whereby it is important to analyze the air temperature, precipitation, relative humidity, wind speed, etc. [13–15].

Urban green spaces and their associated benefits are important for sustainable urban development as far as ecological, economic, and social aspects are concerned [16]. The urban forest is a complex ecosystem, closely related to the urban ecosystem [17]; correct planning of green areas provides protection against strong and prevailing winds, being able to modify and direct them through obstruction, deflection, and conduction. Thus, it is possible to improve the local climatic condition and develop a landscape that is accessible to all [18].

The use of vegetation in urban areas will always play an effective role in the psychological and landscape sense. In the context of the urban landscape, each vegetation type has its specific characteristics such as color, shape, and height, as well as leaves and flowers that modify the environment through ornamental properties, making each urban area a pleasant and striking landscape. In the psychological sense, these spaces provide a feeling of wellbeing, improved mood, and social relationship, especially when associated with leisure and sport infrastructures [19].

All the benefits to health and environment provided by urban forests, such as biodiversity protection and mitigation of climate change, are extremely relevant and should always be considered [20]. These benefits cover five major areas that are interconnected: economic, social, health, visual, and aesthetic. These services include air filtration, carbon sequestration, storm water attenuation, energy conservation, reduction in global warming, microclimate maintenance, reduce temperatures through shading, wellbeing improvement, encouragement of outdoor activity, noise absorption, and preservation of biodiversity.

A study demonstrated changes in air quality due to urban trees [21]. The urban forest acts as a filter, removing pollutants and reducing the polluting effect. Trees absorb these gases through their leaves and transform them into biomass. This mechanism has a direct influence on air quality improvement and is characterized as a benefit provided by urban forestry. Furthermore, alongside plant roots, there are bacteria that also absorb polluting gases, degrading them and resulting in nutritious elements available to plants (Figure 1) [22].

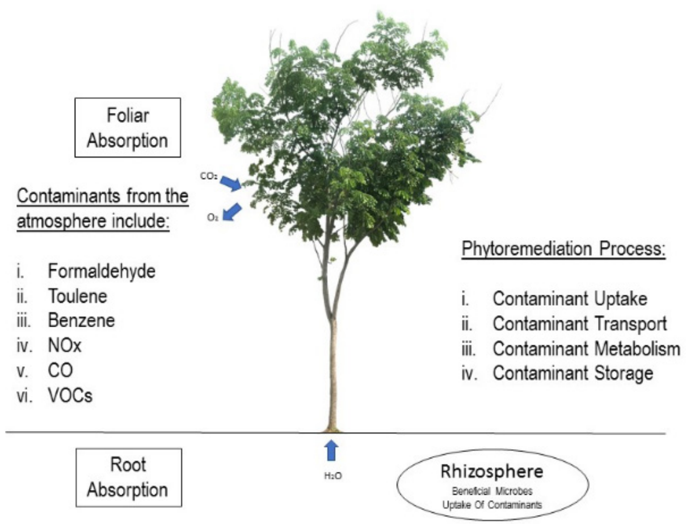

Figure 1. Absorption of gases by plants. Adapted from [22], with permission from IntechOpen, 2013.

The concept of the greenhouse effect emerged in the late 19th century; however, it was in the second half of the 20th century, with growing environmental concern, that it became popular. The concern with the emission of greenhouse gases is the related increase in the Earth's temperature, changing the climate and compromising the survival of several species [23].

Trees in the urban infrastructure are an important vehicle for carbon sequestration, removing carbon dioxide from the atmosphere. Green spaces remove more carbon than they introduce to the atmosphere [24,25]. Thus, a forest in a green space maximizes carbon sequestration [26].

According to [27], vegetation in the urban environment can greatly improve the urban microclimate, as well as mitigate the heat island effect, by reducing summer air temperatures. Therefore, increasing vegetation in the urban context can be an effective way of mitigating the urban heat island (UHI), thus benefiting urban centers [28]. A decrease in temperature is achieved through trees that provide solar protection, affect air movement and heat exchange, absorb solar radiation, and cool air through evapotranspiration processes. It should be noted that urban parks may extend their cooling potential and decrease ambient temperatures in adjacent urban zones depending on the thermal balance of the overall area under study [29].

A study investigated the role of trees on NOx pollutant dispersion in a real neighborhood in Pamplona (Spain) [30]. Aerodynamic and deposition effects were studied by computational fluid dynamics (CFD) modeling. Different scenarios, changing the tree-foliage, were simulated. The results suggest that the distribution of pollutants is modified by the inclusion of new trees not only in the precise location, but also in nearby locations, which is dependent on each particular case and the surrounding conditions [31].

In biomechanics, the tree is considered a structural element subject to gravitational and wind forces; thus, it is necessary to determine its physical and mechanical properties, in addition to its stability and the normal and shear stresses [32,33]; accordingly, biomechanics researchers have developed or assessed devices and procedures for testing the presence of decay [2,34–40].

Knowledge of the phytosanitary status of trees helps to prevent accidents and is particularly important in large urban centers where the trees are more likely to fall and cause human and material losses. This knowledge is possible using methods capable of reproducing, with a high degree of confidence, the real health condition of the tree without the use of invasive tests that will harm it [40–47]. In this scenario, it is also important to highlight how pollution of the urban area is harmful to the health of the trees [48].

To better consider the phytosanitary and stability conditions of the tree, it is necessary to consider the predisposing, inciting, and contributing factors that underline the spiral of decline model proposed by [49] (Table 1).

Table 1. Predisposing, inciting, and contributing factors.

Predisposing Factors	Inciting Factors	Contributing Factor	Dendrological Parameters
Urban environment	Drought	Biotic agents	Diameter of breast height—DBH
Soil compaction	Floods		Height of the tree
Genetic potential	Severe pruning		Height of the canopy
Age	Excavation		Height of the stem
Lack of light	Air pollution		Diameter of canopy
Sea proximity	Overwatering		
	Root cuting		

Predisposing factors are those that influence the condition of the tree in the medium or long term, and that are intrinsic to the site or the tree. Inciting factors are those that refer to abiotic or manmade episodes. Contributing factors are those that contribute to accelerating the decline in the phytosanitary conditions of the tree, such as deterioration by biological agents (fungi, virus, nematodes, etc.). These agents take advantage of fragile conditions originating from predisposing and/or inciting factors. As the name suggests, they are preponderant in accelerating the decline and, in most cases, result from multiple causes, not being an inciting factor [49–51].

There are technological tools that have been used to assist the inspection of trees. These tools allow obtaining parameters that can be used in the calculation of the risk of fall, contributing to the decision regarding the maintenance or removal of a tree, considering safety of the community and respecting the need to maintain the environmental services provided by trees to cities [4,6,52]. Nondestructive testing has been used as a quality control tool in the forest industry and urban forest. These techniques are used to infer wood physical and mechanical properties [53].

The objective of this paper was to present a review that focuses on tree health assessment in urban areas, specifically on the methodologies commonly used to detect levels, dimensions, and location of wood deterioration.

2. Urban Tree Health Assessment Methodologies

The history of tree risk assessment as documented in the literature is relatively recent, and the interest surrounding tree risk has continued to grow in recent years [53–56]. Several international research summits have focused on tree risk assessment, the costs associated with not maintaining trees, and the biomechanics of trees as these relate to tree failure potential [57–59]. The latter area of research has arguably been the most active, whereby assessment with knowledge gained from biomechanics research is often used to develop guidelines, techniques, and technologies for gauging tree failure potential.

A wide range of methods have been used to assess urban trees. Researchers' choice of study methods has been influenced by several factors, including scale of the study area, purpose of the study, and availability of information and data. Field surveys, samples, and experiments have primarily been used for analysis where it has been feasible to assess all existing trees. Techniques including GIS, aerial photography, and remote sensing have been used for relatively larger study areas encompassing regions, metropolitan areas, and cross-city, inter-state, and international comparative research [7,60–63]. Tree statics tests were introduced in the 1980s, with the first example performing a tensile static load test, also known as a pulling test [64]. In [65], many results from pulling tests are gathered and discussed using precursors of this field trial proposal. This method has evolved over time, as has the equipment used to apply the load and to measure tree displacements and inclinations [66–70].

Hence, test methodologies are important to provide knowledge about the health, safety, and structural conditions of trees and improve the measurement accuracy [69,71–74]. The visual tree assessment (VTA) is the simplest, oldest, and most economical method for tree evaluation, allowing inspection of symptoms, mechanical damage, and presence of moisture, fruiting bodies, or insects [75,76]. However, it does not always allow the detection of such conditions, especially when it is in its initial phase. In this sense, tomography is an important tool for the location of more fragile areas in the stem, since the location of these areas is fundamental for the analysis of the risk of falling [77].

The digital wood inspection drill is another process to detect defects and quantify internal decay in wood tree. When associated with VTA and ultrasound, it allows a precise verification of the biodeterioration processes. The difficulty to recognize and describe patterns associated with the fall risk or final diagnosis of trees condition is still a challenge to the scientists. This review paper provides information and constructs the body of knowledge acquired on the subject by several scientists. Accordingly, it will be possible to enhance the application of knowledge for this association between diagnosis and fall risk.

Management decisions are influenced by the actual, assessed, and perceived risk surrounding trees. Recommendations based on the findings of the assessment are then passed onto people who ultimately make the final decisions [78].

2.1. Visual Analyses

In visual analyses, three standard inputs are usually considered: the failure potential, likelihood of impact, and consequences of failure [75,76,79–81]. Over the years, several different visual risk assessment methods have been used by arborists and urban foresters.

The parameters considered in visual tree assessment (VTA) include the structural characteristics or dendrological parameters (diameter of breast height (DBH), height of the tree, height of the canopy, species, etc.), type of surroundings (Table 1), indicative signs or symptoms related to biotic or abiotic agents, and details of the phytosanitary status (Table 2). Arboriculturists consider visual tree assessment essential to provide basic information about tree growth performance and stability [82].

Another visual method is the ISA Tree Hazard Evaluation that acts as a guide for collecting and recording tree risk assessment information. This form is for trees receiving a basic risk assessment [75]. Another example is the United States Department of Agriculture Forest Services Community Tree Risk Evaluation. This visual method is designed to assist communities in designing, adopting, and implementing tree risk management programs, as well as in training field staff to detect, assess, and correct hazardous defects in urban trees [79]. The "Static Integrated Assessment" (SIA) method for assessing tree risk [83] was developed after the VTA (visual tree assessment) method and applies established engineering methods to determine tree breakage safety.

Table 2. Indicative signs or symptoms related to visual analysis.

Root	Cavity; Injury; Surface
Stem	Cavity; Injury; Codominance; Inclined; Adventitious; Spheroplast; Included bark; Protuberance
Branch	Cavity; Wound; Codominance; Dense; Dry; Large; Slender
Twig	Adventitious; Dry; Low; Dense
Leaf	Dry; Necrosis; Chlorosis; Small; Large; Perforated; Epinasty
Crown	Dead; Dieback; Transparent; Inclined; High; Low; Unbalanced; Dense
Biotic Agents	White rot; Brown rot; Soft rot; Fumagine; Aphids; Anthracnose; Xanthogaleruca luteola; Termite; Other phytopathogenes
Lesion	Height; Width; Depth; Height above the ground; Distance to the back wall; Thickness of the front wall; Tree diameter at lesion entrance

These methods represent some of the more commonly used approaches for visual assessing risk, but it is important to note that additional analyses are required to complement these results, because it is not always possible to assess health conditions, especially when in its initial phase. The superficial definitions from visual assessment give users/arborists the flexibility to use their expertise in the evaluation; thus, it is necessary to identify whether this imprecision reflects the current uncertainty surrounding the tree risk protocol or if it simply adds unnecessary variability to assessments. To this point, instrumental analysis contributes to reducing variability and increases the current understanding in tree risk assessments [54].

2.2. *Acoustic Tomography*

Although the focus is on acoustic tomography (stress wave and ultrasound) in this work, it is important to emphasize that other methods are also used to obtain internal scanning and imaging in the evaluation of trees.

The idea of applying tomography in the analysis of materials came from medicine, where it is one of the most important diagnostic methods since the discovery of radiographs [84]. In 1978, [85] presented a review of scanning and imaging techniques that, in theory, could be applied to assess deterioration in standing trees. The authors cited microwaves, ultrasound, X-ray and gamma-ray computed tomography, and magnetic resonance imaging as scanning possibilities when specific equipment adapted for use in the field was available. The authors defined X-ray and gamma-ray computed tomography (CT) as very useful to provide two-dimensional density maps related to specific gravity variations that, through interpretation, could detect and differentiate advanced decay, but their main concern, at that moment, was the need for mobile equipment and software with specific requirements. In 1992, [84] described a mobile computed tomography system composed of a radiation source, detectors moving on rails and rotating in the base ring, and a computer controlling the system. This same mobile equipment was proposed by [86] to study the water supply of living trees, in general, and trees damaged by resin extraction, in particular. Computed tomography was the focus of several papers presented at the Symposium on Nondestructive Wood Testing for many years, first directed at standing trees, but later (1989, 1991, 1994) moving on to log, lumber, beams, and poles, probably due to the difficulty of their application for in situ trees. Although CT allows a good internal visualization of the trunk [87], the use of a radiation source has limited practical use and has encouraged the search for other methods that also allow obtaining internal digitization and imaging technologies in the evaluation of rot in standing trees.

As a CT technology, electrical impedance tomography (EIT) was also introduced for medical purposes in 1978 to study pulmonary edema [88]. In recent years, the EIT technique has developed rapidly, and its application has diversified into other areas, such as soil properties, wood deterioration assessment, and plant phenotypic information [89]. EIT has been applied to root evaluations [90–92], as well as to trees [93,94].

As an alternative to tomography using radiation sources, acoustic technologies such as ultrasound and stress wave have been the most studied aimed at applications in image construction [93–97]. Since 2002, with the technology bases already consolidated, studies have been focused on improvement and evolution, including equipment, probes, algorithms, and system optimization, with approaches for better understanding the elastic wave propagation in trunks and application of the anisotropy correction factor [98–102].

Acoustic tomography is a nondestructive technique that can be applied to trees to detect the presence of anomalies or deterioration, where the images can be reconstructed from characteristic parameters of the wave, such as propagation time, amplitude, or spectrum frequency [103]. It is an efficient method; hence, wave propagation is affected by materials with different structural characteristics, meaning different acoustic impedance and, therefore, different velocities [103,104]. The velocity of wave propagation in solids with cavities is decreased because the wave surrounds the cavity, causing an increase in the propagation time [105]. In other words, the mechanical and acoustic properties of the wood are vulnerable to the influence of some factors, because it is affected by defects due to conditions that change the wood structure [103], such as the tree age, health condition, and height of the stem [106,107], or defects induced by irregularities of different natural growth patterns (grain deviation, knots, pockets, resin, etc.), generating differences in material and consequent variation in wave propagation velocity and amplitude of the emitted signal. These factors are mainly determined by anatomical characteristics of the wood, such as the proportion of juvenile and late wood and by the angle of the microfibers of conductive elements. The microfibril angle has a strong correlation with density and modulus of elasticity (MOE), and it has an influence on the stiffness, strength, and dimensional stability of wood [108].

Acoustic techniques have been widely used as a nondestructive method to inspect wood and evaluate their internal conditions. Among these techniques, stress and ultrasound waves are the most popular due to the low cost and portability of the required equipment. Technical difficulties encountered in the past have delayed the development of ultrasound tomography. One example is the attenuation of the wave propagating throughout the material, whereby low-power ultrasound equipment is not able to obtain the proper wave propagation signal to analyze large-diameter trees. Stress waves present fewer problems with attenuation, mainly because they use low frequencies. However, high-power ultrasound equipment overcomes these problems with the advantage over stress waves of enabling frequency control. Control of the frequency used in inspections is very important as it enables tailoring the frequency to the size of the defects to be observed, increasing the accuracy of the process [94,109].

Usually, wood inspection is divided into four steps: detection, location, characterization or description, and action to be taken [110,111].

One study proposed a measurement mesh [99] that nowadays is used in different research groups to construct tomographic images (Figure 2). For this mesh, it is logical to imagine that, when increasing the number of measurement points, there will be an increase in the image accuracy. However, this implies substantially increasing the fieldwork. Considering the most frequently adopted diffraction mesh, with $n = 8$ measurement points (Figure 2), a test made in all directions (Ex: 1–2 and 2–1) will result in 56 routes (8×7). With $N = 16$ measurement points, the number of measurements routes becomes 240 (16×15), and so on. Thus, it is important to evaluate a way to obtain an optimal number of measurement points, improving the image accuracy without excessively increasing the field work.

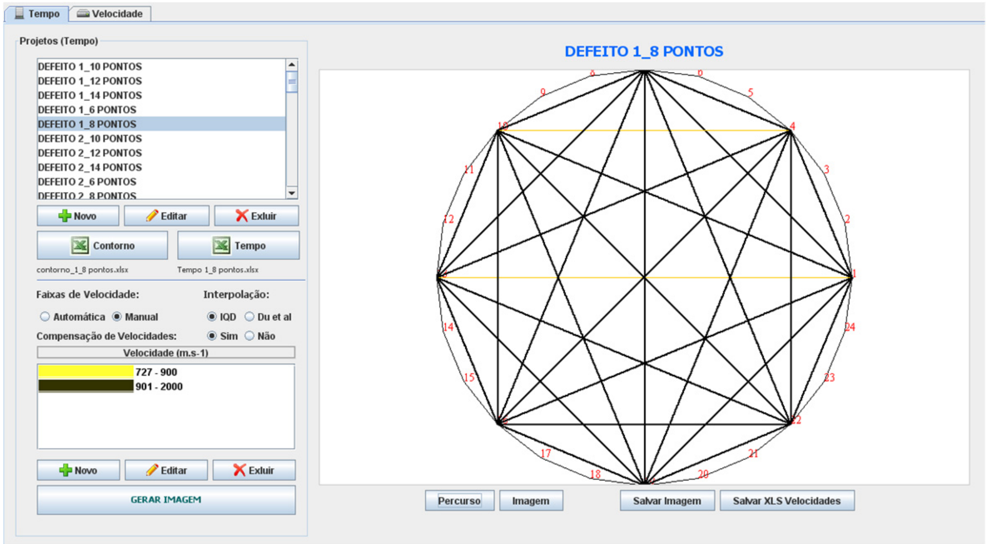

Figure 2. Diffraction mesh with eight measurement points produced by software (ImageWood). Source: Reproduced with permission from Raquel Gonçalves (2021), Nondestructive Testing Research Group Coordinator, School of Agricultural Engineering, University of Campinas, Brazil.

Another study used images generated by ultrasound waves applied to wood logs with artificial holes, whose size and location were known, to compare two different types of measuring grids (reticulated and diffraction grids), concluding that the diffraction grid provided better images than the reticulated grid, when compared to the real image (Figure 3) [112].

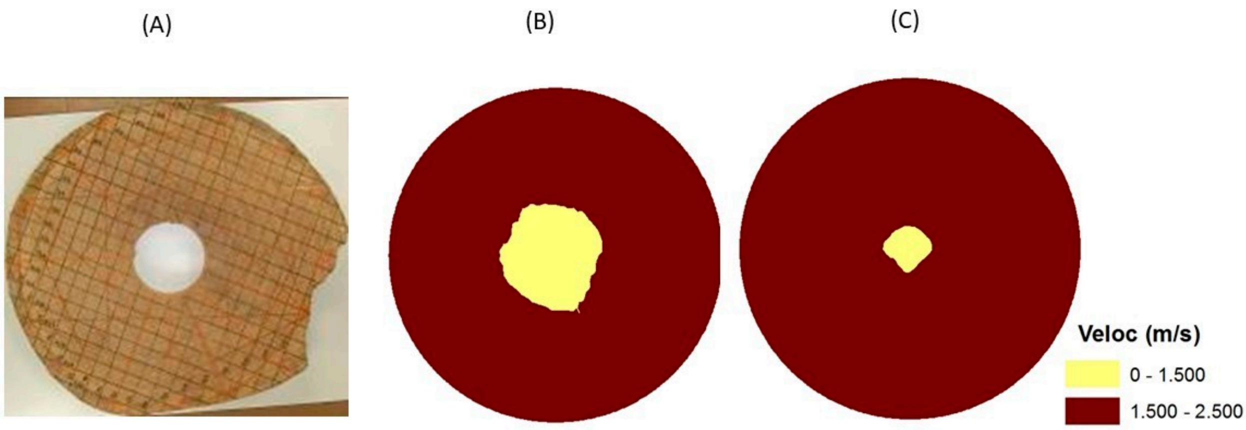

Figure 3. (**A**) Pequia species (*Aspidosperma desmanthum*) with an artificial circular hole. (**B**) Resulting image using a diffraction grid. (**C**) Resulting image using a reticulated grid. Source: Reproduced from [112], whose is deposited in the Scientific and Intellectual Production Repository of University of Campinas [DOI: https://doi.org/10.47749/T/UNICAMP.2011.793973, accessed on 10 November 2021].

With ultrasound tomography, images are generated by associating colors with velocity bands, allowing the visualization of the entire section of the stem under analysis, related to variations of stiffness and/or strength inside the stem. This technique is most sensitive for discs subjected to fungal attacks and is based on the generation of color differentiation images (Figure 4), which represents the wave propagation velocity ranges in the material under inspection. It is important to highlight that, for wood, an orthotropic and heterogeneous material, it is not adequate to use a reference velocity [113–115], being more effective to use, as reference, the maximum velocity obtained in the inspected material itself (Figure 4).

Figure 4. Example of ultrasound tomography image. Source: Reproduced with permission from Raquel Gonçalves (2021), Nondestructive Testing Research Group Coordinator, School of Agricultural Engineering, University of Campinas, Brazil. Legend: Yellow = velocities from 80% to 100% of maximum velocity; Brown = velocities from 50% to 80% of maximum velocity; Red = velocities from 36% to 50% of maximum velocity; Yellow = velocities from 0% to 36% of maximum velocity.

The ellipse-based spatial interpolation proposed by [102] seems to improve tomographic images as shown when comparing the images obtained by [116,117]. Moreover, [102] stated that their approach was able to detect two holes, whereas the work of [116,117] failed to do so.

There has been considerable research on improving techniques that can detect and locate internal defects on wood using images obtained from tomography [102,114,116,118], as well as techniques to quantify the accuracy of the acoustic tomograph instead of using only visual analysis of the produced images [119]. Despite the numerous advantages of acoustic tomography mentioned above, the results of this technique cannot be evaluated without considering the parameters used in the measurement (type of mesh and number of measurement points), in the construction of images (software, interpolation algorithms), and related to the reference velocity to identify the areas inside the trunk (sound wood, deteriorated wood, and cavities). This makes the inspection report require the participation of a specialist or that the equipment be previously calibrated for specific analysis conditions. Therefore, among the challenges to be addressed in acoustic tomography is the recognition and description of patterns, considering both the interference generated by the simplified interpolation method used by the software and the recognition of the areas effectively affected by different types of deterioration. With these improvements, it will be possible to increase the precision and rectify the tomographic image interpretation during the tree health diagnosis.

2.3. Digital Wood Inspection Drill

The density is one of the most important properties for forest industries and for obtaining the stiffness coefficient by nondestructive techniques using velocity of wave propagation. According to [120], wood density is an important qualitative parameter for different uses, because it is correlated with several other wood properties. This management involves not only the handling of raw material still in the forest, but also the yield of the cellulose processing. Wood density is considered a qualitative characteristic in tree improvement programs due to its economic value and high degree of genetic control [121]. Currently, the determination of the basic density involves expensive laboratory tests, which require time and specialized personnel.

An increment borer is the primary and most commonly used tool to manually extract cores from trees for analysis of growth trends based on an inspection of the tree's ring patterns [122–124]. In a recent study, [125] evaluated the use of the drill to infer the density of young eucalyptus destined to pulp production for cellulose. The researchers found a clear trend of correlation weakening as the drill penetration depth increased, which could be attributed to the increased friction acting on the drill axis, with the accumulation of chips generated during drilling.

The digital wood inspection drill is a process to detect defects and quantify internal decay in wood, but only defects with advanced stages of decay can be identified reliably [126]. When associated with the VTA and ultrasound, it allows a precise verification of the biodeterioration processes. The drilling resistance measurement is a semi-destructive test, and the measurement is made by the variation of the torque required by the drill bit to advance. The drill needs to have approximately 5 mm diameter, to capture variations in the material's resistance to perforation without causing damage to the material, whereas it cannot be so thin as to suffer resonance or buckling [127]. As the drill moves through the wood in a linear path, the penetration resistance along its path is measured and recorded. The method has been used in tree inspections and structures since 1988 [128]. The test has been used to identify deteriorated areas in wooden structures [127,129,130], logs, or trees [36,37,131,132].

There is also a growing interest in using the drilling resistance method in genetic improvement programs. A study evaluated the use of drilling resistance for rapid assessment of the relative density of pine wood in progeny tests [133]. A total of 1477 trees were sampled from 14 pine families located at four test sites. They reported weak (R^2 = 0.29) to moderate (R^2 = 0.65) capacity in explaining the variability of the density by the resistance to drilling. Similar results were also reported in [134–136].

3. Biodeterioration of Wood by Fungi and Termites

Xylophages can degrade the wood, leading to tree destabilization and even falls. Many of these attacks occur in the innermost part, making identification, performed solely through visual analysis, inefficient [77]. Termites also cause problems to trees, because of their ability to digest cellulose provided by symbiotic microbiological fauna present in their gut [136,137], but it is important to note that, in Portugal's environmental conditions, termite damage is not as severe as other countries with warmer environments. Usually, infestation starts at the root, building galleries and destroying the heartwood [138]; thus, the attack is slower and less noticeable in the initial state.

The great majority of termites prefer to attack tissues already damaged by fungi, but there are species that can attack healthy wood. Some factors such as humidity and oxygen availability are determinant for the type of infestation. Different types of events may occur during termite diversification, e.g., the external uptake of symbionts or the horizontal transmission of symbionts within different termite species foraging the same area and resources. The diversification of termites toward an optimization of the digestive process, depending on the environmental conditions and type of resources exploited by the termites, is an important factor explaining the flagellate protist communities associated with certain groups of termites [139]. The termite species that is considered one of the most destructive, both for urban afforestation and crops, is *Coptotermes gestroi*, which is characterized as an underground termite [140]. This termite is of Asian origin but has been observed today in many tropical and subtropical regions of the world. Underground termites initiate the attack on living trees from the root; often, although the heartwood is destroyed, the tree shows no external signs of attack [138]. A study pointed out that *C. gestroi* termites can also enter the bark, making pipes and destroying live tree stems [82].

Different studies have contributed to the knowledge of the biology and distribution of these insects, as well as the species with the potential to become pests [141,142]. The wood of the tree stem has its mechanical properties changed upon decay [143]. However, the properties change differently because, in termite attack, galleries are formed surrounded by intact material, whereas, in fungus attack, there are wood modifications dependent on the type of the fungi and on the intensity of the attack. Changes in stiffness and strength are captured by wave velocity propagation variation within the material. Thus, detecting deterioration in trees, particularly when there are no external indicators, is of great interest to forest and urban managers. Therefore, nondestructive methods have become the focus of recent research, and ultrasonic tomography is one of the techniques considered viable, in association with visual analysis, to inspect the phytosanitary state of trees.

Acoustic tomography has proven to be the most effective technique for detecting, locating, and estimating the size and shape of internal defects [144]. One study focused on studying ultrasonic images of wood inoculated with termites, using the variation of the velocity of propagation of the ultrasound waves in wooden discs, as well as the evaluation of their masses during the xylophagous activities [145]. After 195 days of inoculation, it was possible to observe the velocity drop in the wooden discs (Figure 5) caused by the internal galleries generated by the xylophages (termites) [146]. To produce the tomographic images, the minimum velocity obtained in the initial condition was used as a reference to check if there was an increase in the lower-velocity zones [42,145].

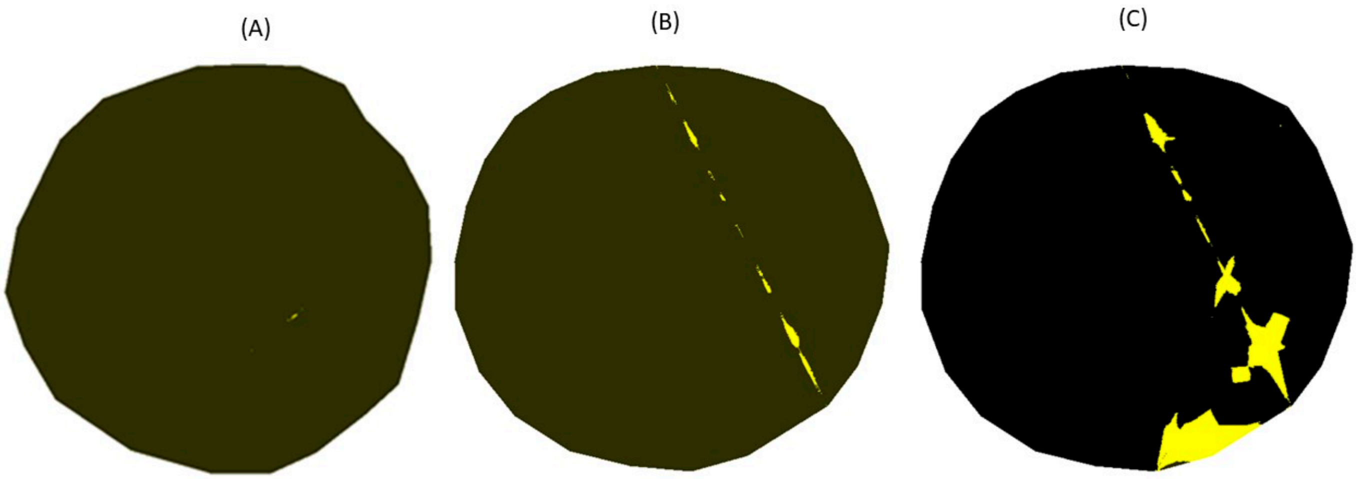

Figure 5. Evaluation of xylophagous attack through ultrasound tomography. Source: Reproduced from [146], whose is deposited in the open Scientific and Intellectual Production Repository of University of Campinas [DOI: https://doi.org/10.47749/T/UNICAMP.2017.989570, accessed on 10 November 2021]. Legend: (**A**) = initial condition of the disc; (**B**) = Condition of the disc 135 days after inoculation with termites; (**C**) = Condition of the disc 195 days after inoculation with termites.

Regarding the colonization of fungi in trees, Ref. [147] described five strategies. The first is heart rot, the biggest cause of wood decay in trees. The second is sap rot, involving colonization of unprotected sapwood due to bark damage. The third is caused by plant stress, mainly on branches and roots; ascomycetes and basidiomycetes are recognized by this colonization strategy, e.g., *Hypoxylon* spp. and *Stereum* spp. The fourth mechanism is called active pathogenesis, in which some rotten fungi can colonize the sapwood, destroying living wood cells. Lastly, the fifth mechanism is caused by desiccation of the upper part of the tree or by drastic fluctuations in wood moisture, either by disease or by altered physiological activity. Under these conditions, some fungi (e.g., various specialized opportunistic ascomycetes and basidiomycetes) tolerate the low or fluctuating moisture content of wood, making this a selective and strategic advantage for plant colonization. A study found that light is the most important variable affecting the formation of fruiting bodies [148].

Biodeteriorating organisms have special morphological, physiological, and behavioral characteristics that make them able to use wood as substrate, shelter, and food.

Decay caused by fungi is the most recurrent; however, ecologically, some wood decay fungi are useful for stability of the forest [149]. Fungi have a primitive morphological constitution, feeding on existing organic constituents because they are unable to synthesize the nutrients indispensable for their diet [150]. Among fungi, there are three main types of enzymatic activity that promote wood rot: white rot, brown rot, and soft rot [151], with the first two being the most common in living trees [138]. Decay in the stem of trees caused by fungi and/or insects reduces their resistance and can lead to fall. Microscopy analysis for two white rot fungi was conducted by [152], revealing that decay patterns were similar. This information is well-grounded and important, because the fungi that most attack living trees are those with enzymatic activity characterized by white rot [138].

White rot is often related to *Armillaria* species belonging to the basidiomycetes class. These fungi spoil without distinction polysaccharides and lignin. During the attack, the wood usually appears whitish. The attack of this fungus causes progressive erosion of the cell wall, as well as of the lignin [153]. Although lignin resists attack from most microorganisms, white rot fungi can efficiently degrade lignin [154]. The degradation is especially detected in the parenchyma cell walls and is characterized by a distinct decrease in the UV absorbance values [155].

Brown rot is caused by fungi of the Basidiomycotina subdivision, mainly in softwood. Rotten wood becomes crumbly, brittle, and darker than healthy wood [138]. These fungi basically consume the cellulose and hemicellulose of the cell walls, keeping the residual lignin. Wood tissue attacked by these fungi becomes rigid and breaks with low strength and unpredictable rupture. Soft rot fungi belonging to the *Asco*mycotina and Deuteromicotina subdivisions preferentially attack cellulose and hemicellulose, rather than lignin, producing cavities in the cell wall. In trees, these fungi are cited as predecessors to the microorganisms that cause the establishment of white or brown rot fungi. Therefore, they are not considered the cause of drastic changes in wood [138].

Ultrasonic tomography can also be used to monitor wood degradation by fungi attack [42]. The authors inoculated *Lentinula edodes* fungi in *Pinus elliottii* discs and monitored the evolution of the biodegradation with ultrasound. The tomographic images allowed verifying the evolution of the degradation (Figure 6). As in the case of the research with termites, the minimum velocity obtained in the initial condition was used as a reference to check if there was an increase in the lower-velocity zones [42,145].

Research results have shown that acoustic tomography has the sensitivity to detect inner areas of fungal-decayed trees [37,156–159]; however, it is also important to note that, under a light microscope, it is possible to verify that the decomposition of naturally decayed wood is greater than that in inoculated wood [160].

The use of ultrasound in the characterization of wood has considerable advantages over conventional compression tests because only one specimen is required to obtain 12 elastic constants, whereas six specimens are required for compression tests [161]. This advantage is even more important in the case of urban trees because obtaining samples from such trees should only be performed when necessary and with the proper authorization. In addition, when it is necessary to obtain branch and root specimens, this question is even more complex, as these parts have small dimensions and are, in general, less assessable [162,163].

Wood characterization through ultrasound is precise in determining the elastic parameters, and it presents correlations with data obtained from destructive static tests. Through ultrasound, it is possible to repeat a test on specimens previously tested and use smaller specimens; moreover, the tests are less expensive and require a reduced number of specimens. The advantages described have motivated several studies in the area [104,163–169].

The employment of a 26-face polyhedron to characterize wood was initially proposed by [170] as a specimen that would enable the complete characterization of the wood using only one sample. Therefore, it is possible to determine the three elastic moduli (EL, ER, and ET), the three shear moduli (GLR, GLT, and GRT), and the six Poisson ratios (νLR, νLT, νRL, νRT, νTL, and νTR) involved in the complete elastic characterization of the wood.

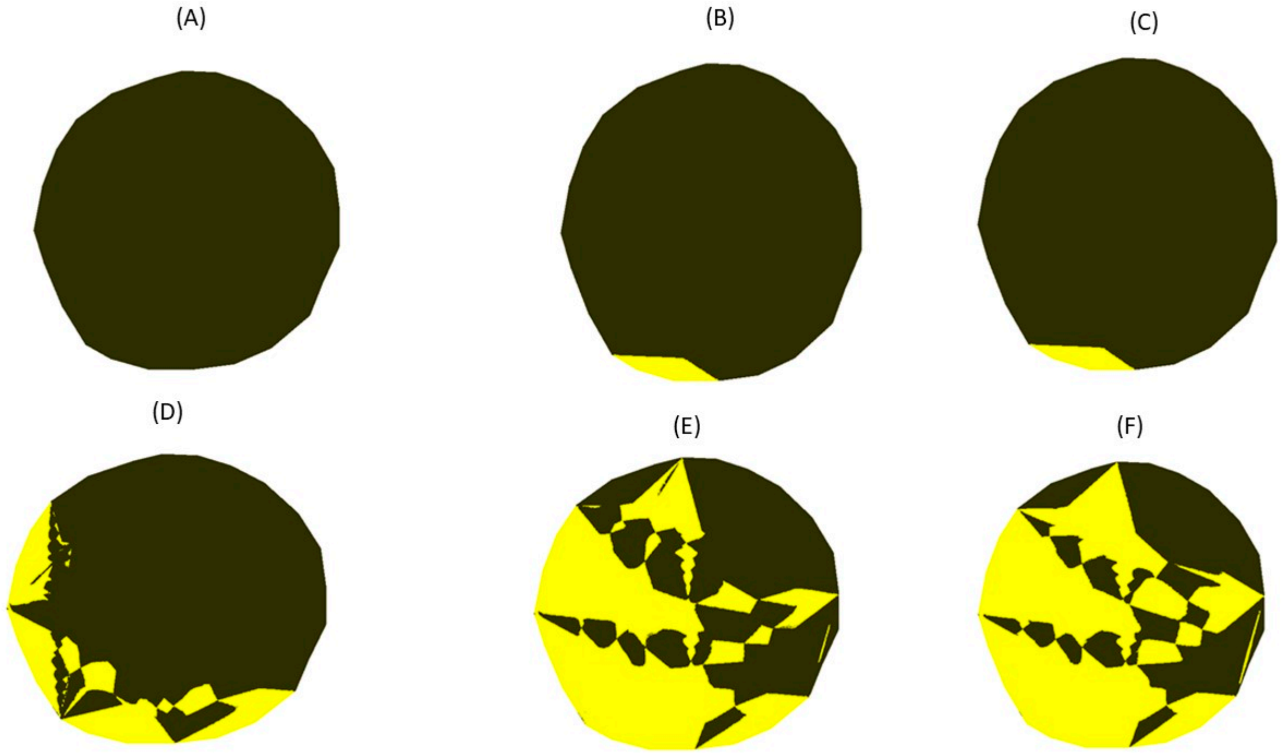

Figure 6. Tomographic images showing the evolution of the biodeterioration caused by fungi. Source: Reproduced from [146], whose is deposited in the open Scientific and Intellectual Production Repository of University of Campinas [DOI: https://doi.org/10.47749/T/UNICAMP.2017.989570, accessed on 10 November 2021]. Legend: (**A**) = initial condition of the disc; (**B**) = Condition of the disc 3 months after fungi inoculation; (**C**) = Condition of the disc 5 months after fungi inoculation; (**D**) = Condition of the disc 7 months after fungi inoculation; (**E**) = Condition of the disc 9 months after fungi inoculation; (**F**) = Condition of the disc 11 months after fungi inoculation.

Ultrasound techniques have been increasingly studied in mechanical sorting applications, wood characterization and inspection [46], and the acoustic tomography of trees [40].

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