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REVIEW

Detection of wood decay and cavities in living trees: a review

Ayodele O. Soge, Olatunde I. Popoola, and Adedeji A. Adetoyinbo

Abstract: It has been established that wood decay and cavities in tree stems contribute significantly to tree failures. Several techniques have been reported by researchers for detecting wood decay and cavities in living trees. These techniques are reviewed in this study under two broad categories: invasive and noninvasive methods. The invasive methods include traditional (decay detecting drill, increment borer, and boroscope), radiographic, acoustic, and electrical resistivity techniques. The noninvasive methods comprise microwave scanning, magnetic resonance imaging, X-ray tomography, and traditional techniques involving the use of mallets. Two or more methods are usually combined to investigate the health status of a tree for comparison and validation of results. The prospects and challenges of the various techniques in diagnosing wood decay, cavities, and other structural defects in living trees are reported. This review aims to help researchers in this field identify areas of further work towards the efficient monitoring and management of forest and urban trees.

Key words: wood decay, tree cavities, internal structural defects, living trees, nondestructive tree testing.

Résumé : On sait que la carie du bois et les cavités présentes dans le tronc sont des causes importantes de défaillance mécanique chez les arbres. Plusieurs techniques capables de détecter la carie et les cavités chez les arbres vivants ont été rapportées par les chercheurs. Dans cet article nous passons en revue ces techniques regroupées en deux grandes catégories : les méthodes invasives et non invasives. Les méthodes invasives incluent les techniques radiographiques, acoustiques et de résistivité électrique traditionnelles (perceuse conçue pour la détection du bois endommagé, tarière et boroscope). Les méthodes non invasives comprennent le balayage en hyperfréquence, la tomographie aux rayons X et les techniques traditionnelles comme l'utilisation du maillet. Deux méthodes ou plus sont habituellement combinées pour déterminer l'état de santé d'un arbre dans le but de comparer et valider les résultats. Les perspectives d'avenir et les défis des diverses techniques pour diagnostiquer la carie du bois, les cavités et les autres défauts structuraux chez les arbres vivants sont rapportés. Cette revue a pour but d'aider les chercheurs dans ce domaine à identifier les sujets de travaux futurs visant à améliorer l'efficacité du suivi et de la gestion des arbres en milieu urbain et en forêt. [Traduit par la Rédaction]

Mots-clés : carie du bois, cavités dans le tronc des arbres, défauts structuraux internes, arbres vivants, évaluation non destructive des arbres.

1. Introduction

The presence of wood decay and cavities in tree stems has been widely reported as the primary cause of tree failures that often lead to loss of human lives and enormous damage to property, especially during stormy weather (Johnstone et al. 2010; Soge 2019; Soge et al. 2019). Besides, the economic and ecological values of a living tree are negatively impacted by wood decay and cavities, as claimed by Soge et al. (2018). In combating these challenges, the role of accurate and reliable techniques for detecting internal structural defects in trees cannot be overemphasized. Several authors have reported diverse methods for sensing defects in trees. These methods can be grouped into two broad categories: invasive methods and noninvasive methods (Lawday and Hodges 2000). The invasive methods involve exposing the wood either by removing the bark discs or in extreme cases by drilling holes into the wood to probe for evidence of decay and cavity (Lawday and Hodges 2000). However, the noninvasive methods allow the probing of the internal structure of the tree through the aid of sensors and other probing devices without exposing the wood or drilling holes into the tree (Lawday and Hodges 2000). One crucial drawback of invasive methods is that the holes drilled into the wood tissue expose the tree to fungi invasion and encourage the spread of any compartmentalized infection to healthy wood — a possible phenomenon when increment borers and drills with the capability of creating deep holes are used (Toole and Grammage 1959; Lawday and Hodges 2000).

The primary examples of invasive methods for identifying decay and cavities in standing trees include the traditional technique (involving the use of tools such as a decay detecting drill, increment borer, and boroscope), X-ray or gamma-ray radiographic techniques, acoustic techniques (those using ultrasonic and stress-wave devices), electrical resistivity techniques, acoustic tomography, and impedance tomography (Weihs et al. 1999). Some examples of noninvasive methods reported by researchers are microwave scanning (Martin et al. 1987), magnetic resonance imaging (Muller et al. 2001), X-ray tomography (Habermehl 1982*a*, 1982*b*), and traditional techniques involving the use of mallets (Dolwin et al. 1998).

In this study, a literature review of the different methods for detecting wood decay and cavities in living trees is reported. This review aims to highlight the prospects and challenges of the

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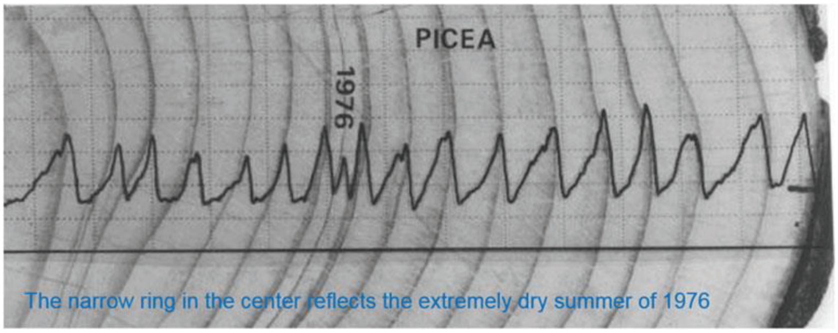
Fig. 1. Resistance drilling profile obtained from a Norway spruce (*Picea abies* (L.) Karst.) showing density variations inside tree rings (Rinn et al. 1996). [Colour online.]



various techniques towards helping researchers in this field identify areas of further work.

2. Invasive and noninvasive methods for wood decay and cavity detections in living trees

2.1. Traditional technique

The traditional technique is a visual inspection of trees for external signs of decay usually undertaken by experienced arboriculturist to ascertain whether further inspection is necessary (Kennard et al. 1996). The external signs of decay in trees include dead cambium, deadwood in the crown, exposed wood with decay, swollen trunks, cracks, and sunken areas (Dolwin et al. 1998). The traditional technique also involves the use of some specialized tools such as mallets, decay detecting drill, increment borers, and borescopes.

The resulting sound from a mallet striking a suspect surface can be interpreted with experience to acquire some information on the presence and extent of wood decay. This is a noninvasive method undertaken with an inexpensive tool (Dolwin et al. 1998). A decay detecting drill (also known as the resistograph method) penetrates the sound tree with a constant drilling pressure, speed, and rotation (Johnstone et al. 2007; Nowak et al. 2016; Goh et al. 2018). The turning moment (or torque), which is equal to drilling resistance, is recorded graphically and relatively to the drilling depth (Goh et al. 2018). An abrupt change in spacing between the lines on the resistograph indicates the presence of wood decay (Goh et al. 2018). Figure 1 shows an example of a drilling profile obtained from Norway spruce (*Picea abies* (L.) Karst.) revealing density variations inside tree rings caused by earlywood and latewood zones (Rinn et al. 1996). The narrow ring in the centre reflects the arid summer of 1976 (Gao et al. 2017). The resistograph method can provide useful quantitative information when used simultaneously with other qualitative techniques, such as acoustic tomography, electrical resistivity, and ground-penetrating radar (Feio et al. 2007; Li et al. 2012; Vössing and Niederleithinger 2018).

The increment borer is a standard forestry tool that consists of a cavity tube with a screw thread at one end. It is usually used to extract a core of wood from a tree trunk, which can then be investigated for the evidence of discolouration or decay along the wood cross-section (Mattheck et al. 1995; Gao et al. 2017; Goh et al. 2018). The increment borer is highly invasive because its head is typically 9–10 mm in diameter and, thus, exposes the tree to fungi invasion (Dolwin et al. 1998). A borescope provides a remote visual inspection of the interior of a tree for the presence of wood decay. Like the increment borer, it involves the drilling of numerous holes into the xylem (or sapwood) (Goh et al. 2018); its accessories include a small video camera and zoom lenses for visual documentation (Goh et al. 2018).

2.2. Radiographic technique

The radiographic technique is an invasive method for sensing decay and cavities in trees using an X-ray or gamma ray radiation. The wood samples can be obtained destructively (harvesting the trees and cutting wood cross-sections) or nondestructively (extraction with increment borer) under laboratory experiments (Tomazello et al. 2008). The radiographic technique involves measuring the attenuation of X-rays or gamma rays at their transmission through the wood samples under examination (Ouis 2003). Wood decay is detected by a decreasing wood density resulting from the biodegradation of the wood cell wall (Osborne et al. 2016). A significant drawback of the radiographic technique is that it is potentially dangerous owing to radiation hazards coupled with the vast electric power consumption of the radiation device (Ouis 2003; Goh et al. 2018). The transportation of the radiographic equipment to the field is also cumbersome, since a suitable vehicle is required (Ouis 2003). These drawbacks have restricted the radiographic technique to urban and rural streets and to parks in cities where old and valuable trees must be regularly inspected for potential hazards (Ouis 2003). The radiographic technique is also applicable in sawmills for the automatic determination of the optimum cutting strategy for each log (Bucur 2003).

Santini et al. (2019) applied the radiographic technique to investigate the microscopic decay process in five tropical trees: *Lafoensia glyptocarpa* Koehne (Mirindiba rosa), *Poincianella pluviosa* (DC.) LP Queiroz (Sibipiruna), *Pterocarpus rohrii* Vahl. (Aldrago), *Rhamnidium elaeocarpum* Reissek (Saguaraji), and *Trichilia claussenii* C.DC. (Catigua). Visual signs of wood deterioration, such as fruiting bodies, white mycelial mass, and drastic pruning, were observed in the trunk and root regions of the trees. Wood core samples comprising sound-wood zone, decay zone due to xylophagous fungi, and barrier zone were extracted with metal probes and analyzed for their microdensity and chemical composition using X-ray densitometry (XRD) and X-ray fluorescence (XRF), respectively. The results obtained confirmed the presence of degraded cell wall fibre and vessels obstructed by mycelial mass in the wood decay zones. Besides, the XRF results revealed an excess concentration of both iron (Fe) and manganese (Mn) in the decay zones. The vital role of Fe and Mn in the oxidative reaction of the wood degradation process has been reported by Illman and Bajt (1997). Moreover, the wood density values in the decay zone were significantly lower than those of the sound-wood zone, except for *R. elaeocarpum*, as displayed by the XRD results. For the barrier zone, the wood density values were higher than those of sound-wood and decay zones for all tree samples except for *T. claussenii*. The excellent performance of the proposed method in analyzing microscopic decay process is an indication of its huge potential for diagnosing and monitoring wood deterioration. However, the main limitation of this technique is the difficulty involved in extracting thin wood samples (1.5 mm) from extremely degraded trees for X-ray analysis (densitometry) and XRF (chemical traces). This challenge can be overcome by considering wood samples of a higher thickness (2–3 mm).

2.3. Acoustic technique

The acoustic technique for decay detection in trees involves the use of sonic devices, which measure the transit time of a pulse of ultrasound or a stress wave across a tree stem. Any deviation from the expected transit time suggests a peculiarity or degradation of a wave path. Ultrasonic waves typically take a longer time to travel through a decayed tree than a healthy tree due to signal attenuation by the decayed wood (Wilcox 1988; Bethge et al. 1996; Axmon 2000). Ultrasonic tree testing tools exploit this phenomenon by measuring the increased transit time when ultrasonic waves evade decay within a tree trunk. However, the interpretation of the data acquired from this technique was unable to offer accurate information on the location and extent of decay in a tree trunk (Lawday and Hodges 2000). This shortcoming can be overcome by combining the acoustic technique with other more efficient methods such as increment core, drilling resistance, and fractometer, to improve the accuracy of the results (Lin and Yang 2015). Moreover, the velocity of sound in wood is dependent on specific properties that are altered by wood decay, such as modulus of elasticity (MOE), moisture content, and density (Dolwin et al. 1998). Additionally, the presence of high moisture content in the tree stem increases the attenuation of ultrasonic waves (Sakai et al. 1990).

The acoustic technique involving the use of ultrasonic and stress-wave devices is classified as an invasive method, since the ultrasonic device is generally used on wood exposed by the removal of bark discs, whereas the stress wave operates via screws inserted a short distance from the wood (Dolwin et al. 1998). Although the acoustic technique can offer comprehensive information on the wood quality, it may be unable to distinguish between decayed wood and bacterial wet wood or between decay and cavities in a tree (Johnstone et al. 2010). Also, single-pulse ultrasound and stress-wave equipment is expensive (Johnstone et al. 2010). The focus of ultrasonic wood characterization has been on wave velocity (v), which decreases in the case of a decayed tree (Ouis 2003).

Wave velocity can be expressed as

$$v = \sqrt{\frac{E}{\rho}} \quad (\mathrm{m/s}) \tag{1}$$

where E is the modulus of elasticity (N/m), which is a measure of the strength of the wood, and ρ is the wood density (kg/m^3). The MOE of a decayed wood is relatively lower than that of sound wood, resulting in the reduction of the wave velocity. It has been verified that velocity is dependent on factors such as tree species, moisture content, temperature, and sound wave direction (Mishiro 1996). However, it is difficult to translate the velocity of sound to physical properties because wood is an anisotropic material (Socco et al. 2004; Bucur 2006*a*; Maurer et al. 2006; Schubert et al. 2009).

Krajnc et al. (2019) implemented an acoustic technique for the detection of internal red heartwood in European beech (*Fagus sylvatica* L.) and butt rot in Norway spruce using ultrasound velocity and damping. Ultrasound measurements were carried out on the standing trees using a point-to-point pulse PL-200 ultrasound device (Proceq, Schwerzenbach, Switzerland) in two horizontal planes: the stump level and 0.5 m above the stump level. The standing living trees were also felled and assessed in the field for the presence of internal structural defects. The potential of ultrasound velocity and damping to predict the presence of internal defects was examined using a binary logistic regression. Similar prediction accuracies (0.72 and 0.76 in beech, and 0.83 and 0.82 in spruce) were recorded for both ultrasound velocity and damping. The results obtained also showed a marked decrease in the radial ultrasound velocity in trees of both species with internal structural defects. Conversely, an increase in the signal damping was recorded in both European beech and Norway spruce with internal defects, confirming the potential of ultrasound damping in early wood decay detection. However, further work is required to characterize the relationships between tree properties, i.e., the size and characteristics of internal structural defects and stem geometry, and the damping of ultrasound waves.

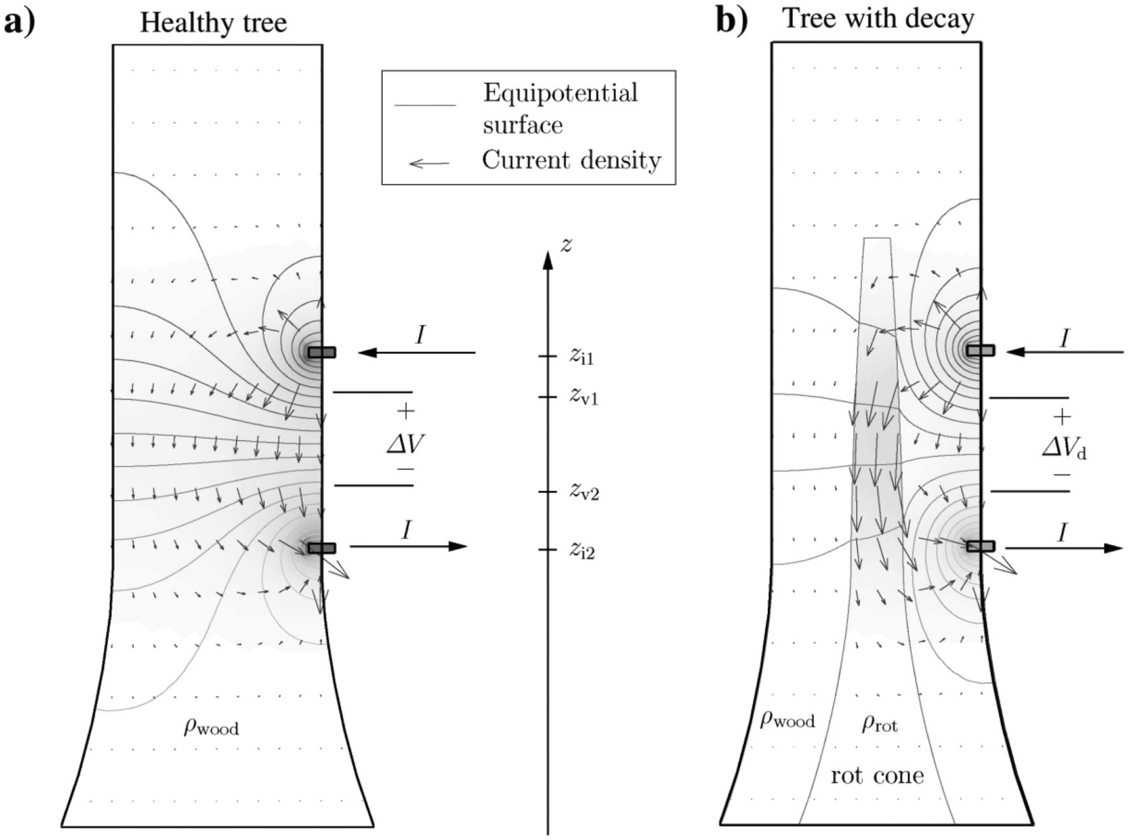
2.4. Electrical resistivity technique

The electrical resistivity technique has been demonstrated by several researchers to be suitable for the early detection of wood decay and cavities in living trees (Butin 1995; Larsson et al. 2004; Martin 2009; Soge et al. 2018, 2019). The critical factor determining the electrical resistance of a tree is the concentration of mobile cations, which is usually very different between sound and degraded wood (Johnstone et al. 2010). It has been observed that in the region adjacent to wood decay, the concentration of cations in the wood would increase leading to a significant reduction in electrical resistance (Shigo 1991). A noticeable number of ions was produced by decay fungi during the wood degradation process of two plane trees (*Platanus hybrida* Brot.) investigated by Nicolotti et al. (2003). Hydrogen (H) and potassium (K) ions are produced by brown rot and white rot, respectively, and which ultimately decrease the electrical resistivity of a decaying tree (Shortle and Smith 1987). A decrease in electrical resistance for bacterial wet wood was also reported by Nicolotti and Miglietta (1998). Moreover, Martin and Gunther (2013) attributed the low resistivity of the fungi-infected wood to the high moisture content and the varying ion concentration caused by the fungi invasion. It has also been reported that fungi play an essential role in the translocation of ions from the soil to wood (Kirker et al. 2017; Gao et al. 2019). Fungi contributed to the active transport of some ions such as Fe, Mn, and Ca (calcium) from the soil in an inoculated flask into the wood, and an increased concentration of metals is often associated with an increased decay-related mass loss (Kirker et al. 2017; Gao et al. 2019). However, there are fungi activities in wood causing a notable reduction in electrical resistivity values of trees without resulting in decay (Kucera 1985; Soge et al. 2019). This constitutes a limitation to the use of electrical resistivity values exclusively for detecting wood decay in trees (Soge et al. 2019). Hence, it is recommended to validate results using other methods.

Gao et al. (2019) investigated the relationship between wood decay and electrical resistance by systematically examining the changes in the electrical resistance, wood mass loss, moisture content, and ion concentrations in larch and poplar wood progressively decayed by brown-rot fungi. The results showed that the decreasing electrical resistance of decaying wood was related to both the mass loss and the changes in the cation concentrations — Fe, Mn, K, Ca, and Mg (magnesium). Additionally, the degradation of wood was more severe as the exposure time to fungi attack increased, and there was an equivalent increase in the mass loss. It was also reported that the electrical resistance of decaying wood significantly decreased as the exposure time increased. The decrease in the electrical resistance during the decay of wood was accompanied by a rapid increase in the cation concentrations. Also, the moisture content of fungus-treated wood significantly increased to various degrees for decayed wood. However, the effect of the change in the moisture content on the electrical resistance was insignificant compared with that of the cation concentrations.

The relative impedance in situ examination (RISE) method for detecting decay in living trees was reported by Bengtsson (1997). RISE is a four-point electrical resistivity method that exploits the effective resistivity and voltage difference between two points along a trunk to locate defects in living trees. The effective resistivity of a single tree was compared with that of other trees measured under similar conditions (temperature, humidity, site conditions, and time of year) to detect wood decay. Larsson et al. (2004) also implemented the four-point resistivity (RISE) method to detect the presence of wood decay in Norway spruce trees. A low-frequency alternating current was passed to the tree stem with a pair of electrodes while measuring the voltage difference with another pair of electrodes to obtain four-point measurements, as shown in Fig. 2. A

Fig. 2. Four-point resistivity method. (*a*) Healthy tree showing that the current is distributed over the whole stem cross-section. (*b*) Tree with decay showing that resistivity is relatively low in the cone-shaped decayed region and that the current is concentrated in the region of decay (Larsson et al. 2004).



lower voltage difference was recorded for a decaying tree than a healthy tree because decay reduces tissue resistivity. Larsson et al. (2004) reported that the resistivities of Norway spruce trees with decay decreased by a factor of two compared with healthy trees. However, the four-point resistivity (RISE) method was unable to detect the exact location and extent of stem decay. This shortcoming was investigated by Soge et al. (2018, 2019) by implementing a four-point electrical resistivity technique to detect the presence, location, and extent of wood decay and hollows (or cavities) in two hardwood trees — candle (*Senna alata* (L.) Roxb.) and almond (*Terminalia catappa* L.) trees.

The electrical resistivity method implemented by Soge et al. (2018, 2019) involved the use of an earth resistivity meter and a modified form of Schlumberger electrode configuration, which employed tiny electrodes with the spacing scaled down to centimetre range. Electrical resistivity measurement of freshly cut sound, decayed, and hollowed trees were taken to obtain their electrical resistivity profiles. These resistivity profiles were applied to detect the location and extent of wood decay and hollows in randomly selected living trees through resistivity curve matching. Soge et al. (2019) reported that the electrical resistivities of decayed candle trees (*S. alata*) were lowered by a factor of five compared with the sound tree. Similarly, the electrical resistivities of hollowed candle trees (*S. alata*) were increased by a factor of four compared with the sound tree. Additionally, the electrical resistivities of almond trees (*T. catappa*) with decay decreased by a factor of 10 compared with the healthy tree (Soge et al. 2018; Soge 2019). Likewise, the electrical resistivities of almond trees (*T. catappa*.) with cavities increased by a factor of three compared with the healthy tree (Soge et al. 2018; Soge 2019). The detection points of the resistivity anomalies created by wood decay and cavities in a standing tree provided crucial information on the location and extent of decay and cavities. This was an improvement over the four-point resistivity (RISE) method reported by Larsson et al. (2004). The proposed technique is a relatively low-cost, innovative method developed to adapt an earth resistivity meter, initially designed for the ground survey, to measure tree resistivity (Soge 2019). Additionally, the resistivity technique implemented is a nondestructive method, since it does not endanger the tree to the invasion of fungi and other decay-forming organisms (Pellerin and Ross 2002). This was made possible through the use of locally fabricated tiny electrodes, with a diameter of 0.382 cm, which could easily be inserted into the tree stem without drilling a hole, unlike the case of shigometer electrodes where a narrow hole is drilled towards the centre of the stem (Larsson et al. 2004).

Goncz et al. (2018) demonstrated that the electrical resistance method using four electrodes was highly reliable in detecting red heart in beech trees (*Fagus sylvatica*) of diameter 40–60 cm. The presence of red heart — a visual defect in beech wood — was identified with a measured voltage drop of 1/3 to 1/5 of that measured on sound beech wood. However, the method failed to offer reliable information on the extent of red heart. This technique can be developed further either by taking several measurements along the length of the tree trunk or using measurements closer to the ground.

2.5. Tomographic methods

Tomographic methods are the least invasive methods for assessing internal decay in trees (Bucur 2005) apart from X-ray tomography and radar tomography, which are classified as noninvasive methods (Larsson et al. 2004; Johnstone 2010). Additionally, tomographic techniques have also been demonstrated to be effective for the nondestructive estimation of sapwood and heartwood width, since sapwood has a lower resistivity than heartwood owing to its higher moisture content (Bieker and Rust 2010; Humplik et al. 2016).

Sonic tomography (SoT), an example of acoustic tomography, is a technique for generating an image of the internal structure of a solid object by recording differences in the speed of sound wave transmission. SoT measures the velocity of sound waves through the wood, which depends on the MOE and the wood density. Brazee et al. (2011) reported that decay causes a decrease in the MOE and wood density.

Acoustic tomography can detect internal decay, locate the defects, and estimate their size, shape, and characteristics (Bucur 2005; Wang et al. 2007, 2009; Deflorio et al. 2008; Lin et al. 2008, 2013; Wang and Allison 2008). Detection of wood decay using acoustic tomography is based on the principle that stress-wave propagation is sensitive to wood degradation. Generally, stress waves travel at a lower velocity in decayed or degraded wood than in sound wood. They are capable of circumventing hollows or cavities, thereby increasing the transmission time between two testing points (Wang and Allison 2008; Ostrovsky et al. 2017). A decrease of about 85%–90% of the average velocity of the stress-wave transmission is an indicator of a hollow or of wood decay in a tree trunk (Fakopp Enterprise Bt. 2015; Ostrovsky et al. 2017). In addition, SoT determines relative strength loss (Rinn 2011; Lin and Yang 2015). A decreasing velocity of the ultrasonic propagation could be indicative of fungal invasion of the wood cell wall since ultrasonic velocity is related to the density and dynamic elasticity modulus (Bucur 1995). SoT has also proven to be very suitable for the early detection of wood decay (Wilcox 1988; Bauer et al. 1991).

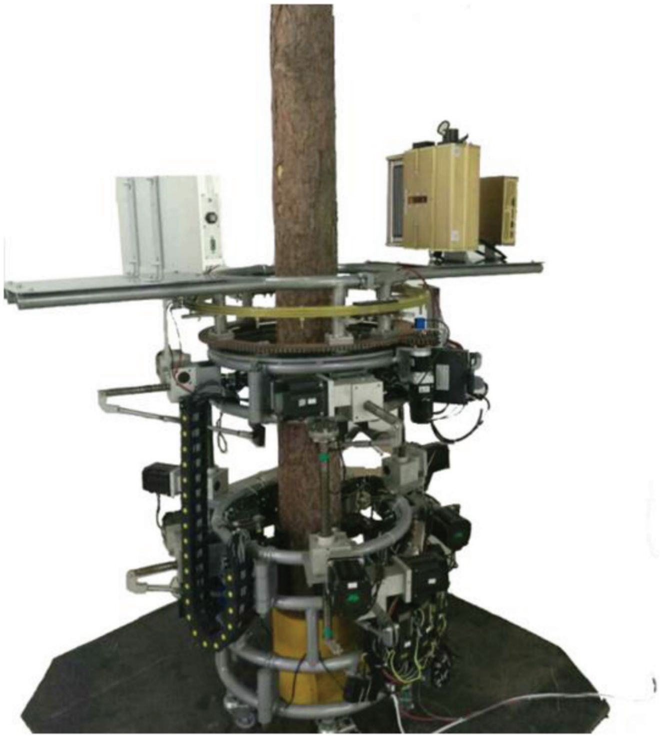
Ostrovsky et al. (2017) investigated the effectiveness of the acoustic tomography technique in sensing internal structural defects in extensively damaged urban trees of five species: Norway maple (*Acer platanoides* L.), European chestnut (*Castanea sativa* Mill.), eastern red cedar (*Juniperus virginiana* L.), Japanese cherry (*Cerasus serrulata* (Lindl.) G. Don), and western red cedar (*Thuja plicata* Donn. Ex D. Don). The sample trees were felled, and a thick disc was cut from each tree for laboratory testing. The tomogram on fresh sample discs was constructed for every cross-section using the Fakopp 3D acoustic tomograph tool comprising 10 sensors placed around the trunk section disc in a horizontal plane during testing. Visual assessment was also conducted on the urban trees to evaluate the accuracy and reliability of the tomography technique. Different kinds of structural defects were visually determined: heartwood and sapwood decay, internal and lateral cracks, ring shake, and hollow. The acoustic tomography inspection accurately determined structural defects in all disc samples examined. Concerning damaged area determination on tomograms, western red cedar samples displayed the highest accuracy of 95%, while Norway maple exhibited the lowest accuracy of 86%. The total accuracy of acoustic tomography was determined by estimating the area and location of the damage. An average accuracy of 83% was recorded for all 15 samples tested. Contrary to the earlier report by Liang et al. (2008) that acoustic tomogram usually underestimates heartwood decay, Ostrovsky et al. (2017) observed overestimation of the damaged area on four of the five samples with heartwood decay. On the other hand, acoustic tomograms underestimated the damaged area due to large hollows on four of five Japanese cherry and Norway maple samples. The underestimation by tomograms was due to difficulty in calculating the velocity of the stress waves accurately as they travel around the hollows (Fakopp Enterprise Bt. 2015; Ostrovsky et al. 2017).

Traditional SoT is not accurate in diagnosing near-surface defects in a tree trunk (Qiu et al. 2019). To overcome this limitation, Qiu et al. (2019) developed an innovative tomographic technique incorporating mechanical waves (e.g., acoustic wave and stress wave) and electromagnetic waves (e.g., laser beam) for sensing defects both at the near-surface and centric position in a tree trunk. The acoustic-laser approach was applied experimentally to examine tree trunks with an air-hole fabricated at the centric position and air gaps sited at 5–50 mm near the tree surface. Experimental results confirmed that the developed method was able to detect accurately the central air hole and the air gap situated at 5–20 mm below the tree surface. Hence, the proposed tomographic method exhibited a higher accuracy and reliability than conventional SoT in spotting near-surface defects in tree trunks.

Lin et al. (2016) reported the diagnosis of decay damage in ironwood living trees (*Casuarina equisetifolia* L.) using acoustic tomography. The authors adopted the lateral impact vibration approach and transversal stress-wave velocity tomography to detect the location and extent of wood deterioration in 15 decay-damaged ironwood street trees of about 30–50 years old with average diameter at breast height (DBH) of 42.2 cm. The stress-wave velocity tomography information (two-dimensional image) of cross-sections of the decay-damaged trees was compared with that of sound ironwood trees of similar age and a DBH of 39.2 cm. The experimental results obtained showed that the average minimum stress-wave value, $V_{\min}$, of the trunks in decay-damaged trees (1404 m/s) was markedly lower than that of the sound trees (1636 m/s). Thus, the $V_{\min}$ value of the sound trees was regarded as the standard value for diagnosing decay-damaged trees using a stress-wave velocity tomogram. A positive correlation was recorded between the transversal stress-wave velocity values and the diameter of the sound tree trunks. The authors were able to identify the location and extent of wood deterioration in the decay-damaged ironwood living trees using both the stress-wave velocity tomogram and related stress-wave velocity maps of decay-damaged and healthy trees. The faster lateral impact vibration method was employed for the preliminary assessment of decay status or state of health.

Electrical impedance tomography (EIT) can detect wood decay at the early stage, which may not be detected by acoustic tomography (Brazee et al. 2011; Weihs et al. 1999). EIT provides the resistivity image of the wood under investigation by determining its electrical conductivity (Brazee et al. 2011). The electrical impedance decreases due to an increased conductivity as moisture accumulates in the decayed wood from fungal colonization (Brazee et al. 2011). EIT was utilized by Bieker and Rust (2010) to examine wood decay in European ash (*Fraxinus excelsior* L.) trees injected with *Trametes versicolor* (L:Fr.) Pilát. EIT precisely determined the location of incipient decay even without noticeable variations in density. Nevertheless, the possibility of losing low-resistivity changes in the tomogram's colour spectrum may cause incipient decay to be invisible in the tomogram (Humplik et al. 2016). This shortcoming can be overcome by combining EIT tomograms with directly measured electrical resistance values of the wood, as demonstrated by Humplik et al. (2016). Statistical parameters of EIT data sets with values of electrical resistance of heartwood were employed to enhance heartwood rot diagnostics in Norway spruce (*Picea abies*) (Humplik et al. 2016). Sapwood proportion values were also detected using the tomograms. It was confirmed that the sapwood proportion decreased as the decayed area in the radial cut enlarges. The reduction in sapwood proportion was due to the creation of reaction zone — a defensive mechanism against the spread of decay as fungi invade the sapwood (Oliva et al. 2012; Humplik et al. 2016). The sapwood proportion specified by a tomograph can serve as an additional pointer to rot presence and growth. Besides, the use of EIT data sets and a sapwood proportion facilitated the clear identification of sound trees. The proposed technique accurately diagnosed both medium-sized and large areas of decay in Norway spruce. However, the large number of sensors and sophisticated electrical circuitry required and the time-consuming nature of the measurements make EIT expensive,

Fig. 3. A computerised tomography platform for the nondestructive testing of living trees (Ge et al. 2018). [Colour online.]



tedious, and unattractive for routine monitoring of decay (Goncz et al. 2018; Soge et al. 2019).

Computerised tomography (CT) can employ acoustic, electrical resistance, and thermal or radar techniques to analyze the internal structure of wood (Johnstone et al. 2010). For electrical resistance and acoustic measurements, sensors are usually placed around a tree (from 8 to 16 but occasionally more), and multiple measurements are gained by sending a signal from one sensor to the others (Gilbert and Smiley 2004; Bucur 2006*b*). CT instruments produce cross-sectional images of the stem via a computer programmed with complex conversion algorithms.

Thermal imaging with an infrared camera scans for wood defects but cannot accurately quantify the amount of wood decay (Catena and Catena 2008). Images are species-specific. This method is based on the phenomenon that the existence of decayed wood tissue or cavities is related to the surface temperature of the tree (Ouis 2003). Thermography cannot assess residual wall thicknesses (Catena 2003). Thermal imaging has the advantage of being noninvasive. It can detect wood decay in large tree roots or the root collar (Catena 2003; Catena and Catena 2008).

Medical CT has been reported in the literature to be useful for analyzing the internal structural characteristics of wood (Jacobs et al. 1995; Livingston 1999). However, the software system for medical CT is not directly applicable to reconstructed wood images owing to the complexity and diversity of wood (Ge et al. 2018). To overcome this inadequacy, Ge et al. (2018) constructed a CT imaging system based on X-ray fan-beam scanning. Figure 3 shows the CT tomography platform developed for the nondestructive testing of living trees. The wood imaging system was used to examine the internal structure of four different kinds of wood — laminated wood, multiknot logs, large-diameter logs, and small-diameter logs — consisting of diverse macroscopic structures, such as knots, cracks, and tree rings. The sectional images of wood obtained from the scanning data revealed some vital information about the intrinsic properties of wood, including the location, dimension, and number of cracks, the number of knots and tree rings, and the growth law for the formation of early and late wood.

Koddenberg et al. (2020) demonstrated three-dimensional investigation of soft-rot-decayed conifers (*Picea abies* and *Pinus sylvestris* L.) and the angiosperm (*Fagus sylvatica*) wood using X-ray microcomputed tomography (XμCT) in a laboratory testing. The sapwood samples of the conifers and the angiosperm were examined after 8, 16, and 24 weeks of soft-rot exposure. Tomographic imaging of the decayed wood was performed with a commercially available cone-beam XμCT system. The fungal-induced degradation patterns observed in tomographic images were compared with those obtained using a scanning electron microscope (SEM) with an energy-dispersive X-ray spectroscopy (EDX) module for validation purposes. XμCT images of soft-rot-decayed wood provided less detailed information than the SEM images owing to limitations in resolving power, tomographic noise, and the weak X-ray attenuation of the wood material caused by the degradation of cell wall material. However, the XμCT images revealed some degradation features of soft-rot decay, such as cell deformations in earlywood and cavities in the thick wall of latewood cells (Schwarze 2007). Besides, the XμCT offered useful information on the distribution of fungal-driven inorganic particles (mostly calcium oxalates) in the decayed wood. The combination of XμCT and SEM–EDX is a promising tool for analyzing soft-rot deterioration in wood.

2.6. Nuclear magnetic resonance (NMR)

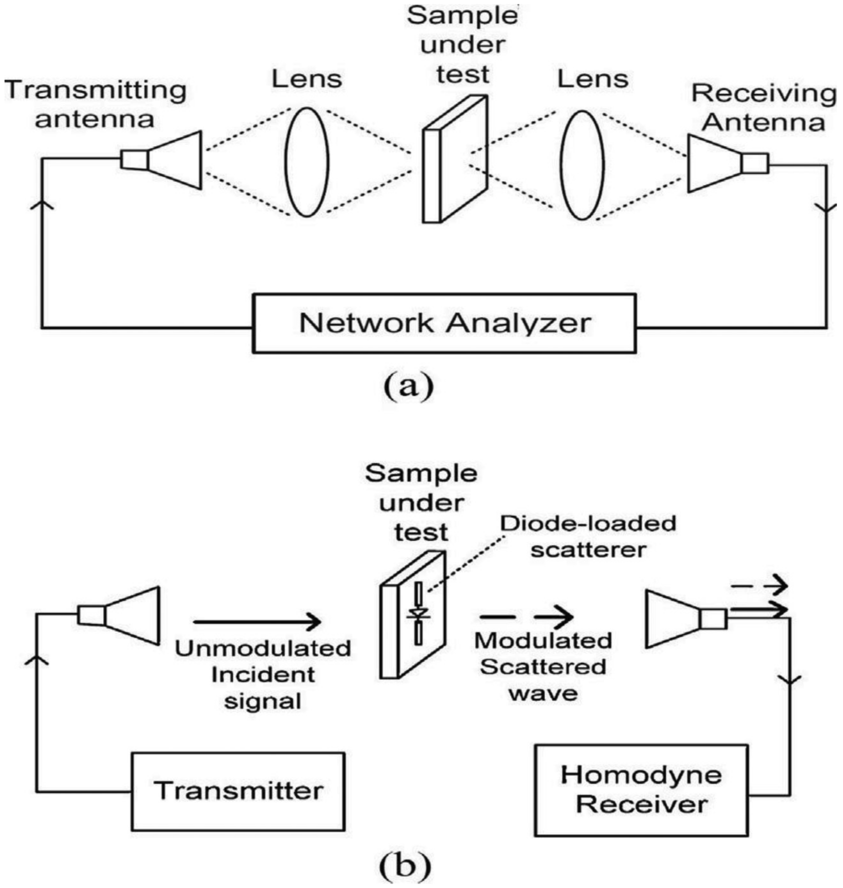
Nuclear magnetic resonance (NMR), also known as the magnetic induction technique, is a noninvasive method for identifying decay and cavities in trees. Generally, this technique involves the use of inductive coils and eddy current to map the passive electromagnetic properties (PEPs) of a material, such as conductivity, permeability, and permittivity (Goh et al. 2018). The NMR system consists of excitation coils that generate the primary electromagnetic field, which then induces an eddy current in the material under investigation to have magnetic field perturbations, also known as the secondary magnetic field. The eddy current is induced in the material due to the PEPs of the material itself. The secondary magnetic field is acquired by the receiver of the NMR system to assess the PEPs' distribution of the tested material (Zakaria et al. 2013). Measurements of NMR are based on the resonance frequency, the magnitude of the signal proportional to the density of the nuclei, the spin–lattice and the spin–spin relaxation durations, the diffusion coefficient, the flow velocity, and the spin–spin coupling time (Araujo et al. 1992). These parameters, in turn, depend on tree species, moisture content, physiological parameters of the wood, and measurement factors including the Larmor precession frequency, and temperature (Bucur 2003).

The chief advantage of the NMR technique, besides being noninvasive, is that the method is contactless (Zakaria et al. 2013). Hence, the galvanic coupling between the tree and the NMR device is not required. However, the NMR technique being a new technology has not been thoroughly investigated in wood science and technology (Goh et al. 2018). Also, the utilisation of the NMR technique may possibly be limited by the high cost of the equipment (Bucur 2003; Goh et al. 2018).

Magnetic resonance imaging (MRI) can be applied to determine the freshwater within a wooden specimen (Araujo et al. 1992; Muller 2001), and it provides excellent and spatial high-resolution information about the morphology and pathology of fresh wood samples in a noninvasive manner (Kucera 1985; Hall et al. 1986*a*). MRI has also been successfully implemented for imaging wood samples (Hall et al. 1986*b*; Wang and Chang 1986; Chang et al. 1989; Flibotte et al. 1990; Olson et al. 1990).

Muller et al. (2001) reported that MRI could accurately and reliably detect fungal decay at an early stage. This was demonstrated using a beech wood sample (*Fagus sylvatica*) infected with the brown rot fungus *Coniophora puteana* (Schum.) Karst. cultured on an agar medium in a sterile glass bottle. The wood sample was

Fig. 4. Two measurement configurations in the microwave technique: (*a*) focused beam and (*b*) modulated scattering technique (Kaestner and Baath 2005).



examined 12 and 26 days after incubation using MRI, which was able to detect areas containing freshwater attributed to fungal activity 12 days after incubation. Thus, MRI was useful in identifying the early stages of fungal decay in wood before any visual evidence. Brown rot fungi decompose cell wall carbohydrate into carbon dioxide and water, resulting in the increased moisture content of the infected wood sample (Muller et al. 2001). With moisture variation inherent in wood, the MRI technique is particularly suited for detecting internal features of wood (Chang et al. 1989).

2.7. Microwave scanning

Microwave scanning or imaging is a noninvasive technique for studying physical properties of wood and for diagnosing wood decay, hollows, or cavities, and other defects in trees. Microwaves are electromagnetic waves with speed and attenuation dependent on the propagating medium, especially its electric permittivity or dielectric constant, which in turn depends on the moisture content and density (Martin et al. 1987). The microwave signal transmission through trees is usually attenuated due to absorption and scattering by the wood tissue (Ulaby and Jedlicka 1984; Choffel 1999; Goh et al. 2018). It has been reported that microwave scanning can be applied to determine the physical characteristics of wood (e.g., density, moisture content, and slope of grain) and the detection of defects from the estimation of attenuation, dephasing, and degree of polarization of microwaves (Martin et al. 1987).

The two principal measurement configurations in the microwave technique are free-space transmission in a focused beam and near-field probing using a modulated scattering technique, as shown in Fig. 4. Kaestner and Baath (2005) developed a microwave system based on the focused beam concept for locating knots in the tree trunks. In this system, the polarization measurements were made using a vector network analyzer connected to a wide-band horn antenna. It was reported that the system could diagnose fungal attacks and cavities in trees.

The noninvasive nature of the microwave technique and the use of relatively small antenna are the principal advantages of the method (Bucur 2003; Goh et al. 2018). However, the difficulties of applying microwave imaging to wood material arise from inherent material properties, such as the anisotropy, heterogeneity, and the presence of natural defects in wood (Larsson et al. 2004; Goh et al. 2018).

2.8. Ground penetrating radar methods

Ground penetrating radar (GPR) is potentially an accurate method for detecting decay in hardwoods (Butnor et al. 2009). GPR uses an antenna to propagate short bursts of electromagnetic energy in solid materials and measure the two-way travel time and amplitude of reflected signals. GPR detects wood decay by measuring the degree of reflectivity of a short radar signal at the boundary between the sound and decayed parts, which have different electrical and magnetic properties (Ouis 2003). Georadar or radar tomography is constituted by the images generated from the reflection of electromagnetic waves at the sound-decayed wood interface (Nicolotti et al. 2003).

The GPR methodology is a noninvasive technique that exploits the variable electromagnetic properties (i.e., dielectric permittivity) of the wood in living trees (Butnor et al. 2009). Decayed wood has a characteristic dielectric permittivity, which differs from that of sound wood owing to the difference in their moisture

Table 1. A summary of the invasive and noninvasive techniques for detecting wood decay and cavities in living trees.

Technique	Principles	Advantages	Disadvantages
Invasive methods			
Traditional technique (Kennard et al. 1996; Lawday and Hodges 2000; Nowak et al. 2016; Goh et al. 2018)	Visual inspection of trees for external signs of decay and cavities using specialized tools such as decay detecting drill, increment borers, and borescopes.	Suitable for preliminary investigation and can be combined with noninvasive techniques for result validation.	Holes drilled into the wood tissue expose the tree to fungi invasion and encourage the spread of any compartmentalized infection to healthy wood.
Radiographic technique (Ouis 2003; Osborne et al. 2016; Goh et al. 2018; Santini et al. 2019)	Wood decay and cavities are detected by a decreasing wood density resulting from the biodegradation of the wood cell wall.	Highly effective for analyzing microscopic decay process.	Potentially dangerous owing to radiation hazards coupled with the vast electric power consumption of the radiation device.
Acoustic technique (Bethge et al. 1996; Axmon 2000; Lawday and Hodges 2000; Johnstone et al. 2010)	Wood decay and cavities are diagnosed by measuring the increased transit time (or decreased wave velocity) when ultrasonic waves evade decay and cavities within a tree trunk.	Provides detailed information on the wood quality.	Unable to offer accurate information on the location and extent of decay in a tree trunk. Ineffective in differentiating between decayed wood and bacterial wetwood, or between decay and cavities in a tree. Not a low-cost method.
Electrical resistivity technique (Kucera 1985; Shortle and Smith 1987; Nicolotti et al. 2003; Soge et al. 2019)	Increasing concentration of mobile cations in the decayed region causes a significant reduction in electrical resistance of the decayed wood.	Suitable for the early detection of wood decay and cavities in living trees. Capable of identifying the location of wood decay and cavities in hardwood trees.	It is essential to validate results using other methods because there are fungi activities that lower electrical resistivity of trees significantly without causing wood decay. This constitutes a limitation for this technique.
Acoustic tomography (Bucur 2005; Lin et al. 2008, 2013; Wang et al. 2007; Lin and Yang 2015; Ostrovsky et al. 2017; Qiu et al. 2019)	An image of the internal structure of the wood is captured by measuring the velocity of sound wave transmission. Sound waves travel at a lower velocity in decayed or degraded wood than in sound wood.	Able to detect internal decay, locate the defects, and estimate their size, shape, and characteristics. Determines relative strength loss of the decayed or degraded wood.	Not accurate in diagnosing near-surface defects in a tree trunk.
Electrical impedance tomography (Brazee et al. 2011; Gao et al. 2019; Bieker and Rust 2010; Humplik et al. 2016)	The resistivity image of the wood under investigation is produced by determining its electrical conductivity. The electrical impedance decreases due to an increased conductivity as mobile cations and moisture accumulate in the decayed wood from fungal colonization.	More effective than acoustic tomography in sensing incipient wood decay. Suited for the nondestructive estimation of sapwood and heartwood width.	Expensive, tedious, and unattractive for routine monitoring of decay.
Noninvasive methods			
Nuclear magnetic resonance (NMR) (Bucur 2003; Goh et al. 2018; Zakaria et al. 2013)	The passive electromagnetic properties (PEPs) of wood such as conductivity, permeability, and permittivity are mapped using inductive coils and eddy current. The PEPs distribution of the tested wood is analyzed to diagnose internal defects.	Apart from being noninvasive, it is contactless–galvanic coupling between the tree and the NMR device is not required. NMR is efficient in identifying the early stages of fungal decay in wood before any visual evidence.	High cost of equipment may hamper its utilization.
Microwave scanning (Martin et al. 1987; Choffel 1999; Bucur 2003; Larsson et al. 2004; Goh et al. 2018)	Microwave signal transmission through trees is usually attenuated due to absorption and scattering by the wood tissue. Wood decay, cavities, and other internal defects in trees are detected from the estimation of attenuation, dephasing, and degree of polarization of microwaves.	It is a noninvasive technique and can be applied to determine the physical characteristics of wood (e.g., density, moisture content, and slope of grain).	The inherent material properties of wood such as the anisotropy, heterogeneity, and the presence of natural defects in wood may constitute difficulties in applying microwave imaging to wood materials.

Table 1 (*concluded*).

Technique	Principles	Advantages	Disadvantages
Ground penetrating radar (GPR) (Nicolotti et al. 2003; Ouis 2003; Butnor et al. 2009; Xiao et al. 2018; Giannakis et al. 2020)	GPR detects wood decay by measuring the degree of reflectivity of a short radar signal at the boundary between the sound and decayed parts which have different electrical and magnetic properties.	GPR method can accurately diagnose both incipient and advanced wood decay and cavities in tree trunks. It is a noninvasive method and effective in estimating the volume of cavities.	High-resolution frequency-domain methods are required for detecting wood layers.

content and density (Nicolotti et al. 2003). Miller and Doolittle (1990) reported that GPR accurately located knots and incipient brown rot in four different angiosperm tree species. A good correlation was observed between high dielectric values and the decayed inner core of two *Platanus hybrida* (Nicolotti et al. 2003). GPR, as a qualitative technique, can be combined with other complementary methods to obtain additional quantitative information (Vössing and Niederleithinger 2018). For instance, Macchioni et al. (2013) demonstrated the application of radiography to examine critical locations in a large section of wood mapped with GPR. Butnor et al. (2009) claimed that the GPR method was effective in estimating the volume of cavities in three conifer species. It was also discovered that exterior wood decay, cavities, and dry trunks had exceptional electromagnetic properties different from other defects.

Giannakis et al. (2020) developed a robust GPR system for examining the internal structure of tree trunks and diagnosing tree decay associated with emerging infectious diseases – ash dieback (*Hymenoscyphus fraxineus*), acute oak decline, and *Xylella fastidiosa*. The internal structure of trees was qualitatively reconstructed using a detection framework based on a modified Kirchhoff migration (Lehmann and Green 2000) and reverse-time migration (Leuschen and Plumb 2001). It was demonstrated through numerical and laboratory measurements that common-offset a GPR commercial antenna combined with the proposed detection outline is a promising candidate for diagnosing emerging infectious diseases. The laboratory measurements were carried out on tree samples of almost equal size with a diameter of 35–45 cm and comprised artificially shaped decay. The moulded decay was filled with wet sawdust to replicate liquid-filled chambers, which are indications of acute oak decline. The laboratory results confirmed that the proposed detection scheme effectively reconstructed the shaped decay and accurately diagnosed both early and advanced tree decay. Moreover, the suggested detection framework can easily be implemented using any commercial GPR system with the least operational and computational requirements (Giannakis et al. 2020).

The combination of GPR and laser scanning radar was employed to precisely detect internal abnormalities in trees by Xiao et al. (2018). Radar data were acquired from *Salix babylonica* L. using the TRU System (Treewin Corporation), which consists of a SIR 3000 GPR module with a 900 MHz centre frequency antenna. A comprehensive radar gram of the preferred trunk elevation was obtained by placing the antenna against the trunk of a tree and moving it circumferentially. Image analysis was conducted on three samples from two trees. Following a sequence of radar data pre-processing phases, inner anomalies such as decay and cavities were detected in the trees using the Hilbert detection algorithm. The results obtained proved that the Hilbert approach can reduce the error in tree abnormality depth and area estimations by almost 10% and 5%, respectively. According to the authors, the proposed technique is an improvement over other nondestructive testing methods with respect to the accuracy of abnormality depth and area assessments. Generally, a significant drawback of the GPR techniques is their inability to detect thin layers owing to poor resolution in the time domain. This can be overcome using multiple signal classification (i.e., MUSIC) (Li et al. 2018) and other high-resolution frequency-domain methods capable of detecting wood layers.

Table 1 summarises the principles, advantages, and disadvantages of the invasive and noninvasive methods discussed in this review for sensing wood decay and cavities in living trees.

3. Conclusion

The various techniques for detecting wood decay and cavities in living trees have been reviewed in this study. These methods are classified into two broad categories: invasive and noninvasive methods. The invasive methods include traditional techniques (decay detecting drill, increment borer, and boroscope), X-ray or gamma-ray radiographic technique, acoustic techniques, electrical resistivity techniques, acoustic tomography, and impedance tomography. Examples of noninvasive methods are microwave scanning, magnetic resonance imaging, X-ray tomography, and traditional techniques involving the use of mallets.

The traditional method is often combined with other techniques for comparison and validation of results. Although acoustic techniques provide detailed information on the wood quality, they are ineffective in differentiating between decayed wood and bacterial wetwood, or between decay and cavities in a tree. Electrical resistivity methods can identify wood decay and cavities at the early stage in living trees. The electrical impedance tomography is suitable for the estimation of sapwood and heartwood width. The combination of XμCT and SEM–EDX is a promising tool for analyzing soft-rot deterioration in wood. The high cost of equipment may hamper the development of the NMR technique even though it is noninvasive and contactless. Apart from diagnosing defects in trees, the microwave scanning method can also determine the physical characteristics of wood such as density, moisture content and slope of grain. GPR is potentially an accurate method for detecting decay in hardwoods. Besides, the GPR system can analyze the internal structure of tree trunks and diagnose tree decay associated with emerging infectious diseases such as ash dieback (*Hymenoscyphus fraxineus*), acute oak decline, and *Xylella fastidiosa*. The combination of GPR and laser scanning radar can precisely detect internal abnormalities in trees. The GPR method is a potential candidate for further research on nondestructive testing of trees for internal defects owing to its endless capabilities. Additionally, the use of several techniques simultaneously is recommended to achieve a sufficient degree of accuracy, which may be impossible with the use of a single technique.

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