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ORIGINAL ARTICLE

Detection of decay and hollows in living almond trees (*Terminalia catappa* L. Roxb.) using electrical resistivity method

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Abstract A precise and cost-efficient diagnostic technique for detecting decay and other structural defects in living trees is indispensable for the risk assessment and conservation of urban and forest trees. A study was carried out to detect the location and extent of decay and hollows (or cavities) in almond trees (*Terminalia catappa* L. Roxb.) using the four-point electrical resistivity method. Electrical resistivity measurements (ERm) of randomly selected living almond trees were taken using an earth resistivity meter, four probes and a modified form of Schlumberger electrode configuration. The ERm were used to obtain resistivity profiles (RP) of the trees. The RP of freshly cut healthy, decayed and hollowed trees were also obtained. A laboratory experiment was set up to replicate the RP of healthy, decayed and hollowed trees. Wood decay and cavities in trees were detected through RP matching. In comparison to healthy trees, wood decay and cavities in tree stems were detected with relatively sharp decrease and increase in electrical resistivity values, respectively. The extent of the resistivity anomalies corresponds to the extent of wood decay and cavities in trees. This method is applicable to early detection of decay and cavities in hardwood trees.

Keywords Living almond trees · Resistivity anomalies · Resistivity method · Curve matching · Schlumberger electrode configuration

Introduction

One major cause of disaster by trees is the lack of timely intervention in cutting down decayed and hollowed trees before they collapse due to wind pressure. Tree failures frequently lead to loss of human lives and colossal damage to property (Johnstone et al. 2010). Additionally, the ecological value of a standing tree in conserving the environment from the threat of climate change is significantly reduced by wood decay. The economic value of a standing tree is also reduced by wood decay, and such trees are generally left to decompose or are used as fuelwood (Larsson et al. 2004). Detection of tree decay is essential not only to forest management but also to public safety in urban communities (Li et al. 2014). The risk assessment and maintenance of trees growing in forests and urban environments also require the availability of a reliable and accurate technique for detecting decay and defects in living trees.

Several researchers (Rinn 1999; Larsson et al. 2004; Martin and Gunther 2013) have reported that electrical resistivity methods can be deployed to detect wood decay in trees. Wood decay is normally accompanied by a decrease in electrical resistivity due to the increasing concentration of cations in the decayed region (Johnstone et al. 2010). It has been reported that brown rot and white rot release hydrogen ions and potassium ions, respectively, which in turn lower the electrical resistivity of a decayed wood (Nicolotti et al. 2003). In addition, the wood resistivity is affected by wood porosity and texture, which are also altered by the fungi decaying action as claimed by Skaar (1988).

The electrical resistivity methods are often called impedance methods. Electrical impedance tomography (EIT) determines the electrical conductivity within wood

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tissue; as moisture builds up in wood from fungal invasion, conductivity increases, thereby decreasing electrical impedance (Brazee et al. 2010). EIT gives an image of the resistivity of the wood and can identify incipient decay, which would otherwise go undetected by Sonic Tomography (Brazee et al. 2010). However, the large number of sensors and sophisticated electrical circuitry required, and time-consuming nature of the measurements make EIT expensive, tedious and unattractive for routine monitoring for decay (Goncz et al. 2017).

The four-point electrical resistivity (RISE) method was implemented to detect wood decay in living trees by Larsson et al. (2004). Four-point measurements were made by passing a low-frequency alternating current over the tree stem with one pair of electrodes whilst measuring the voltage difference with another pair of electrodes. The effective resistivity of wood depends on water content and temperature making it difficult to use the resistivity of an individual tree for the detection of decay (Larsson et al. 2004). Instead, the resistivity of an individual tree was compared with that of other trees measured under similar conditions, i.e., temperature, humidity, site conditions and time of year. Although the method was able to detect stem decay with a high accuracy, it was unable to provide information on the volume or location of the decay (Johnstone et al. 2010).

The aim of this study was to detect the location and extent of the resistivity anomalies due to wood decay and hollows in living almond tree stems (*Terminalia catappa* L. Roxb.) using the four-point electrical resistivity technique. These hardwood trees are amongst the most common urban trees in the South-West region of Nigeria where this work was carried out. Moreover, these trees constitute a serious threat to human lives and property during strong winds that normally accompany heavy rainfall in the tropical zone.

Materials and methods

Field measurements

Electrical resistivity values of living trees were estimated using the four-point electrical resistivity method (Larsson et al. 2004). Fifty almond trees (*Terminalia catappa* L. Roxb.) of diameter ranging from 420 to 1100 mm were randomly sampled from various locations in University of Ibadan campus, Ibadan, Nigeria. The random sampling of the trees was carried out between 1 June and 30 September 2013. Vertical variation of resistivity with depth, also known as vertical electrical sounding (VES), was carried out on the trees using the Schlumberger electrode configuration with a reduced scale (Reynolds 2011).

The implementation of the four-point electrical resistivity method involved the use of four electrodes which were arranged along the length of the tree stem. A direct current was applied by two electrodes (C_1, C_2) separated by distance AB, and the potential difference between two points was measured by two electrodes (P_1, P_2) separated by distance MN as shown in Fig. 1. Potential electrode separation of 40 mm and 60 mm was used whilst varying the current electrodes positions by 20 mm to increase the depth of current penetration. Generally, the current electrode separation AB is proportional to the depth of current penetration (Herman 2001). Therefore, by increasing the current electrode separation, more of the injected current will flow to greater depths. The sort of electrode separations used in this study requires the use of tiny electrodes to prevent short circuit which may occur if conventional electrodes of typical thickness 14 mm designed for soil resistivity measurement were used.

Tiny electrodes of thickness 3.82 mm were employed for this research work to accommodate the small electrode separations. Electrical resistance values were measured at different points on the trees using Miller 400D digital resistance meter—commonly known as earth resistivity meter for shallow ground survey. The geometric factor K of the electrode configuration was estimated simultaneously using Eq. (1)

$$K = 2\pi\left[\left(\frac{1}{\mathrm{AM}} - \frac{1}{\mathrm{MB}}\right) - \left(\frac{1}{\mathrm{AN}} - \frac{1}{\mathrm{NB}}\right)\right]^{-1} \tag{1}$$

where AM, MB, AN and NB are the separations of the electrodes as shown in Fig. 1 (Reynolds 2011).

Also, the apparent resistivity values ρ_a were computed as

$$\rho_a = R_a K \tag{2}$$

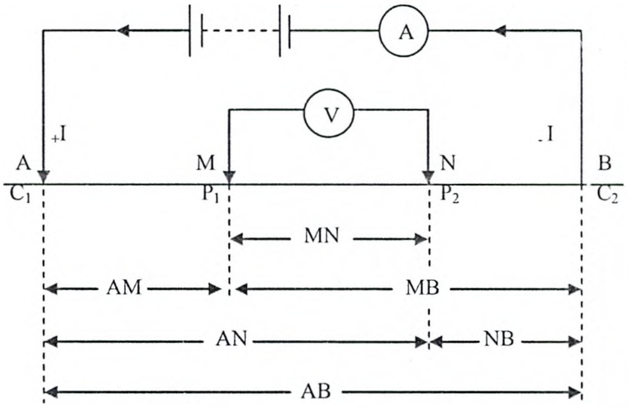


Fig. 1 Generalized form of electrode configuration in resistivity surveys. C_1 and C_2 are the current electrodes, whilst P_1 and P_2 are the potential electrodes. MN, AM, MB, AN NB, and AB are the separations of the electrodes. AB is the current electrode separation, whilst MN is the potential electrode separation

where R_a is the measured resistance value of the tree (Reynolds 2011).

Electrical resistivity values of a log of almond tree of stem diameter 450 mm and comprising decayed and hollowed segments were also obtained (Fig. 2). The tree was cut down after showing visual evidence of internal decay such as (1) exposed wood showing decay due to mechanical damage or broken bark, (2) indications of excessive mechanical stress, e.g., trunk swellings, cracks, sunken areas etc., (3) presence of deadwood or dieback in crown and (4) presence of dead cambium under the bark. The resistivity measurement was taken on the log of wood, immediately the tree was cut down, as it was done on living trees.

Laboratory measurements and modelling

A laboratory experiment was set up based on the field measurements to further investigate the effects of wood decay and hollows on the electrical resistivity profiles of healthy almond trees. This was carried out by modelling varied sizes of wood decay and hollows using a laboratory prototype as a healthy tree replica. The electrical resistivity profiles of the laboratory prototype were applied to detect wood decay and hollows in living trees through resistivity curve matching. The laboratory prototype was fabricated as a wooden hollow cylinder of height 600 mm and diameter 500 mm and filled with compacted sawdust or wood dust, obtained from a wood without decay or defects, to mimic stems of living trees. The cambium was modelled with compacted wet sawdust, whilst the xylem was replicated with compacted dry sawdust. Vertical electrical sounding (VES) was carried out on the laboratory prototype the same way it was done on the trees as described under "Field measurements" section. The resistivity plot of the healthy tree was compared to that of the laboratory prototype for similarity in profile. Once a similarity in profile is established, the resistivity profile of the laboratory prototype serves as a replica for healthy tree.

Furthermore, the extent of wood decay or hollow was modelled into the laboratory prototype that serves as a replica for the healthy tree. This was carried out by using good electrical conductors, e.g., copper wire lump (Fig. 3a) because wood decay process is normally accompanied by an increase in electrical conductivity due to increasing concentration of mobile cations in the decayed region (Goh et al. 2018). A copper wire lump of thickness 50 mm and length 200 mm was placed at 50 mm, 100 mm, 150 mm and 200 mm depths, from the centre of the wire lump to the laboratory prototype surface. Similarly, electrical insulators, e.g., plastic cylinders, were used to create hollows in the laboratory prototype (Fig. 3b) since hollows or cavities in a tree do not conduct electricity (Larsson et al. 2004). A hollow of diameter 80 mm and height 210 mm was modelled into the laboratory prototype at depths 40 mm, 120 mm and 200 mm, from the centre of the modelled hollow to the laboratory prototype surface. Resistivity anomalies were introduced into the laboratory prototype at different depths, and VES was carried out to detect both the presence and location of the anomalies. The effect of the anomalies on the resistivity profiles of the prototype was determined by comparing the resistivity plots obtained before and after anomalies were introduced. The resistivity

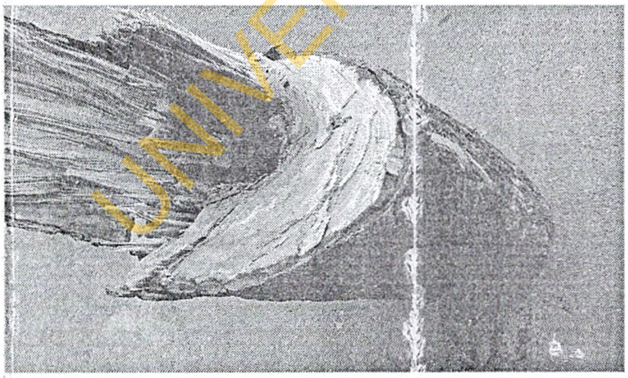


Fig. 2 A freshly cut decayed almond tree with hollow

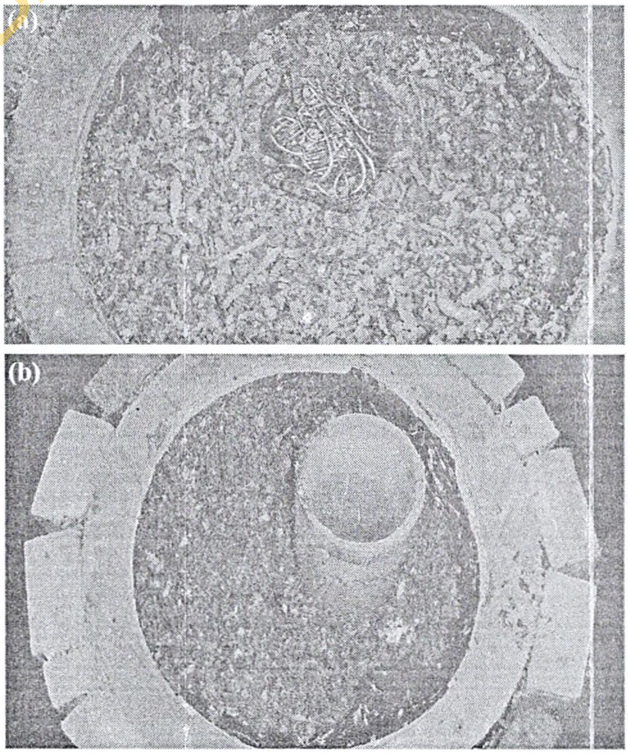


Fig. 3 A laboratory prototype with a a copper wire lump inserted to model wood decay, b a plastic cylinder inserted to model an hollow

profiles of the laboratory prototype with anomalies serve as the replica for those of living trees with decay and hollows.

Furthermore, a collection of 2-D images showing the cross sections of living trees with decay and hollows was developed using the resistivity profiles obtained from the laboratory experiments. The cross section of a healthy tree was modelled by two concentric circles representing the cambium and xylem. The diameters of the concentric circles correspond to the diameters of the tree or cambium and xylem, respectively. Additional circles of different diameters were used to capture decay and hollows in a tree stem.

Results and discussion

Field results

Table 1 shows the resistivity values of four healthy almond trees of similar diameter sited at the same location. The resistivity values of the laboratory prototype are included for comparison. The resistivity values of the healthy almond trees presented in Table 1 contain a major trend—a series of low resistivity values followed by a series of high resistivity values. The low resistivity values represent the cambium, whilst the high resistivity values correspond to the xylem. The diameter of trees 1 and 2 is 520 mm, whilst that of trees 3 and 4 is 509 mm. Figure 4 shows that the resistivity profiles of the almond trees and that of the laboratory prototype are identical. The steep rise in electrical resistivity values from the cambium to the xylem observed in this study was also reported by Bieker and Rust (2010), who estimated sapwood and heartwood width in Scots pine (*Pinus sylvestris* L.) trees using electrical resistivity tomography. All tomograms displayed a distinct pattern of low resistivity at the stem perimeter and high resistivity in the stem centre with a steep increase in resistivity in between (Bieker and Rust 2010). In addition, a similar pattern was observed by Manyazawale and Ostrofsky (1992), claiming that healthy sapwood usually measures lower internal electrical resistance (IER) than heartwood. A marked pattern of lower resistivity values in the outermost stemwood and high resistivity values in the inner stemwood of conifers was reported by Guyot et al. (2013). Therefore, the steep rise in electrical resistivity values from the cambium to the xylem confirmed that the almond trees presented in Fig. 4 were healthy trees. Moreover, the resistivity profiles of the healthy almond trees correlated strongly with that of the laboratory prototype replicating the healthy trees ($r^2 = 0.998$) as shown in Fig. 5. Therefore, the laboratory prototype was a true replica of healthy almond trees of similar diameter.

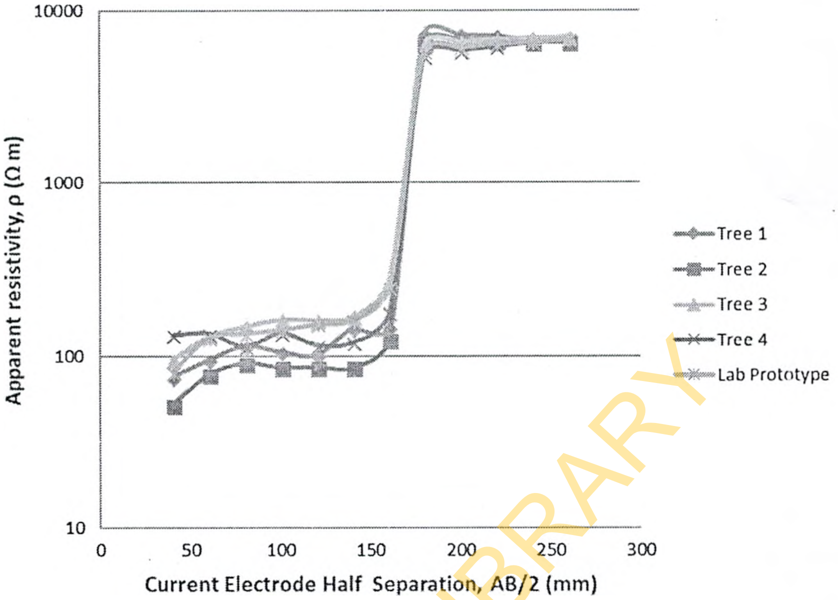
Electrical resistivity values of a decayed almond tree with hollow and of stem diameter 450 mm are presented in Table 2. The resistivity values of a healthy tree of similar stem diameter are included for comparison. Table 2 shows the presence of wood decay in the cambium of the almond tree as represented by a series of lower resistivity values compared to those of the healthy almond tree. The resistivity values of the decayed cambium varied between 12 and 17 Ωm, whilst those of the healthy cambium ranged between 134 and 232 Ωm. Table 2 also shows the presence of a cavity or hollow in the xylem of the almond tree as represented by a series of higher resistivity values compared to those of the healthy almond tree. The resistivity values of the hollowed xylem varied between 10,243 and 14,538 Ωm, whilst those of the healthy xylem ranged between 3621 and 4071 Ωm.

Table 1 Resistivity values of four almond trees with similar diameter

AB/2[a] (mm)	MN[b] (mm)	Resistivity (Ωm)				
		Tree 1	Tree 2	Tree 3	Tree 4	Laboratory prototype
40	40	75.210	52.025	96.133	131.947	81.336
60	40	95.002	78.163	130.942	135.214	128.032
80	40	114.040	90.949	149.383	113.097	135.201
100	40	105.558	85.954	163.614	135.717	142.439
120	40	101.159	86.315	162.734	115.454	153.150
140	40	145.292	85.803	170.400	120.034	162.320
160	60	147.055	124.690	275.109	178.326	249.380
180	60	7338.760	6484.247	6268.920	5417.204	5825.692
200	60	7215.610	6749.083	6579.294	5834.950	6157.670
220	60	7125.132	6710.442	6815.751	6152.566	6425.308
240	60	6738.716	6603.942	6964.273	6487.138	6577.804
260	60	7019.575	6544.566	7011.397	6764.070	6816.513

[a] Current electrode half separation, [b] potential electrode separation

Fig. 4 Resistivity plots of almond trees of similar diameter and their replica



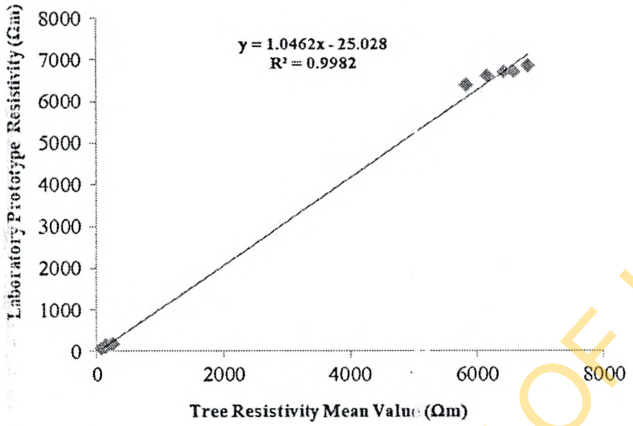


Fig. 5 Resistivity of laboratory prototype versus mean resistivity of almond trees

The in situ measurement of the resistivity values of the freshly cut decayed almond tree with hollow showed that decay causes a significant decrease in the resistivity values of a healthy tree, whilst hollow results in a large increase in the resistivity values. This result correlates with the reports by some researchers who claimed that lowered electrical resistance and resistivity are strong indications of early decay process prior to its visualization (Shortle and Smith 1987; Smith and Shortle 1988). Also, Larsson et al. (2004) reported that cavities or hollows increase stem resistivity because they do not conduct electricity.

Table 2 Resistivity values of a healthy almond tree and a decayed almond tree with hollow

AB/2[a] (mm)	MN[b] (mm)	Resistivity (Ωm)	
		Decayed tree with hollow	Healthy tree
40	40	12.604	133.832
60	40	13.055	184.223
80	40	15.737	208.759
100	40	16.770	231.473
120	40	15.739	153.561
140	40	12.227	160.221
160	60	11,227.738	4037.575
180	60	12,101.415	4071.504
200	60	13,490.318	3949.924
220	60	14,538.275	3724.672
240	60	10,243.442	3620.937
260	60	11,976.283	3742.014

[a]Current electrode half separation, [b]potential electrode separation

Laboratory results

Table 3 contains the electrical resistivity values of the laboratory prototype with a copper wire lump inserted at different depths to model tree decay, which introduced anomaly into the resistivity profile of the prototype. The resistivity values of the laboratory prototype representing a healthy tree (i.e., without anomaly) are also included for comparison. Similarly, Table 4 contains the electrical resistivity values of the laboratory prototype with a hollow created at different depths in the laboratory prototype. The copper wire lump inserted at different depths in the laboratory prototype to replicate wood decay in a tree stem was responsible for the comparatively low resistivity values recorded at the various current electrode half separation,

Table 3 Resistivity values of laboratory prototype with a copper wire lump inserted at various depths with the centre of the wire lump as the reference point

AB/2[a] (mm)	MN[b] (mm)	Resistivity (Ωm)				
		50 mm depth	100 mm depth	150 mm depth	200 mm depth	No anomaly
40	40	23.192*	74.271	76.115	77.025	81.336
60	40	31.837*	116.385	121.962	125.729	128.032
80	40	34.011*	120.902	124.183	129.082	135.201
100	40	130.528	36.031*	130.727	136.622	142.439
120	40	142.916	38.529*	138.225	145.711	153.150
140	40	155.281	40.682*	143.988	157.580	162.320
160	60	241.389	228.051	62.710*	235.902	249.380
180	60	5530.211	5522.906	1451.691*	5510.811	5825.692
200	60	5890.813	5885.748	1542.027*	5850.932	6157.670
220	60	6136.079	6130.182	6121.915	1599.018*	6425.308
240	60	6293.512	6282.065	6275.120	1653.752*	6577.804
260	60	6526.758	6513.719	6502.034	1716.627*	6816.513

*detection point of the copper wire lump, [a]Current electrode half separation, [b]potential electrode separation

Table 4 Resistivity values of laboratory prototype with a modelled hollow at various depths with the centre of the hollow as the reference point

AB/2[a] (mm)	MN[b] (mm)	Resistivity (Ωm)			
		40 mm depth	120 mm depth	200 mm depth	No anomaly
40	40	250.217*	102.320	94.210	81.336
60	40	392.944*	160.501	149.835	128.032
80	40	413.528*	181.285	164.029	135.201
100	40	432.016*	196.092	171.730	142.439
120	40	195.592	472.138*	185.294	153.150
140	40	201.127	500.425*	201.805	162.320
160	60	276.152	760.810*	295.312	249.380
180	60	5938.371	17,490.115*	6019.441	5825.692
200	60	6264.892	6350.283	18,492.072*	6157.670
220	60	6531.533	6601.096	19,289.210*	6425.308
240	60	6698.219	6752.480	19,745.431*	6577.804
260	60	6929.047	6980.118	20,355.119*	6816.513

*detection point of the modelled hollow, [a]Current electrode half separation, [b]potential electrode separation

AB/2, where the resistivity anomaly was detected as shown in Table 3. Additionally, the hollow modelled in the laboratory prototype at various depths resulted in the relatively high resistivity values recorded at the detection points of the anomaly as presented in Table 4. Apart from showing the locations of the resistivity anomalies created by the copper wire lump and hollows, the laboratory results may also provide information on the extent of the resistivity anomalies—an equivalent of the extent of decay and hollows in living trees. The detection points of the resistivity anomalies expressed in terms of the current electrode half separation AB/2 correspond to the diameters of the copper wire lump (i.e., the wood decay replica) and hollows since AB/2 is proportional to the depth of current penetration (Herman 2001).

Wood decay replicated in the laboratory prototypes was detected as resistivity anomalies ranging from 23 to 63 Ωm in the cambium and 1452–1717 Ωm in the xylem, representing a decrease by a factor of 4 when compared with those of the healthy tree replica. Embedded hollows were detected as resistivity anomalies ranging from 250 to 761 Ωm in the cambium and 17,490–20,355 Ωm in the xylem, representing an increase by a factor of 3 when compared with those of the healthy tree replica. Hence, the resistivity profiles of the laboratory prototype with modelled wood decays and hollows obtained from Tables 3 and

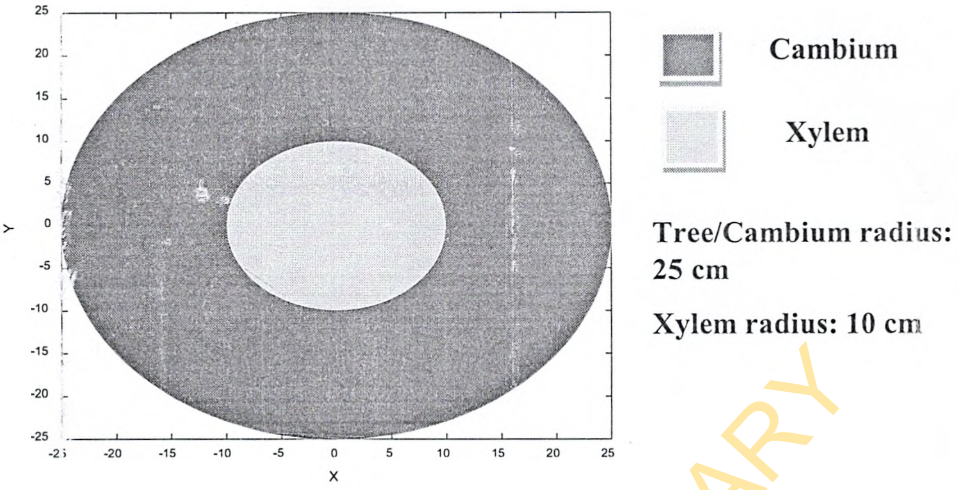


Fig. 6 A 2-D image of the cross section of a healthy almond tree showing the cambium and xylem

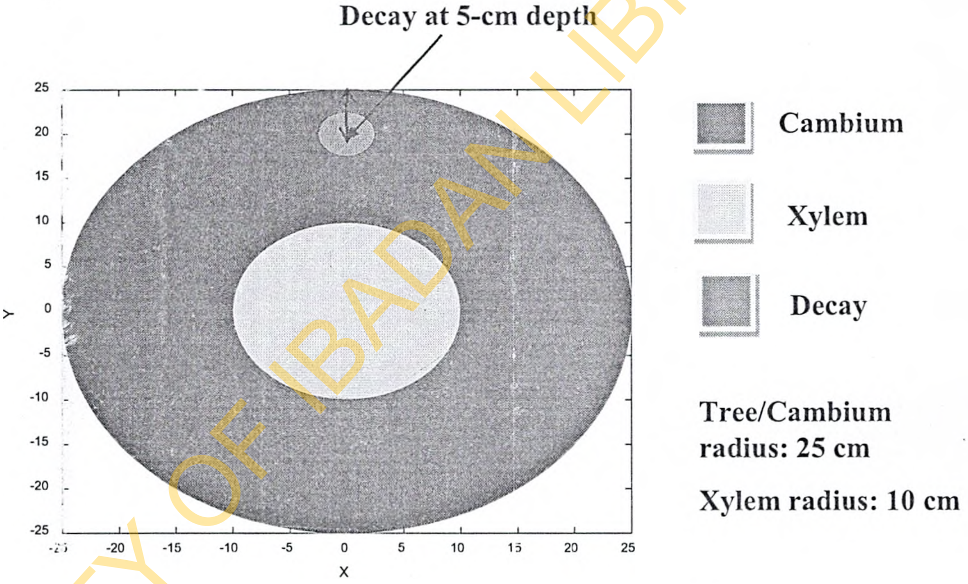


Fig. 7 A 2-D image of the cross section of a decayed almond tree with wood decay of diameter 5 cm located in the cambium at 5 cm depth with the centre of the decay as the reference point

4 serve as a sort of benchmark for detecting decay and hollows in trees through curve matching. For instance, to detect decay or hollow in a tree, the resistivity profile of the tree will be compared to that of the healthy tree shown in Fig. 4, provided they are of similar diameter. If the two resistivity profiles match, it implies that the tree under examination is healthy; otherwise, the tree has decayed or may have hollow sections. The location and extent of the decay or hollow in the tree are determined by comparing the resistivity profile of the tree to those of laboratory prototype with modelled wood decay and cavities, for a possible match provided they are of similar diameter.

The 2-D images of the modelled cross sections of living trees using the resistivity profiles obtained from the laboratory experiments are presented in Figs. 6, 7, 8 and 9. The cross section of an equivalent healthy tree of diameter 50 cm without any decay or hollow is shown in Fig. 6. Figure 7 shows the cross section of a tree with wood decay of diameter 5 cm located at 5 cm depth in the cambium with the centre of the decay as the reference point for depth measurement. The cross section of a tree with a hollow of diameter 14 cm located at 20 cm depth in the xylem is displayed in Fig. 8. Figure 9 shows the cross section of a tree with wood decay of diameter 5 cm located at 5 cm depth in the cambium, and a hollow of diameter 14 cm located at 14.5 cm depth in both cambium and xylem. Moreover, the 2-D images of the modelled cross sections of almond trees apart from evolving from the resistivity profiles of the laboratory prototype also transformed the resistivity profiles from graphs into images, clearly showing the cross sections of comparable trees with the location and extent of the wood decay and hollows highlighted.

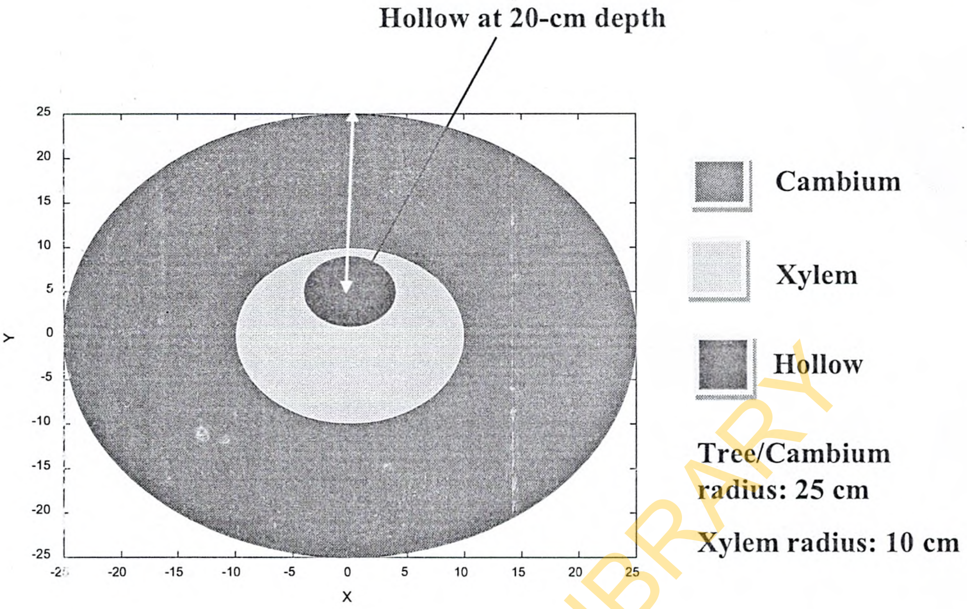


Fig. 8 A 2-D image of the cross section of an almond tree with hollow of diameter 8 cm located in the xylem at 20 cm depth with the centre of the hollow as the reference point

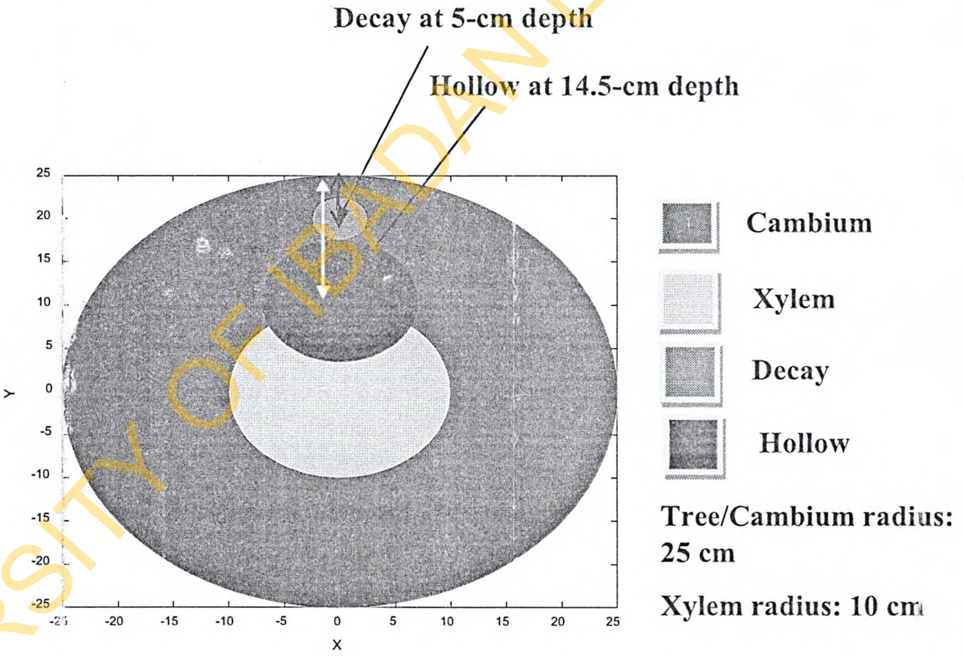


Fig. 9 A 2-D image of the cross section of an almond tree with wood decay of diameter 5 cm located in the cambium at 5 cm depth and a hollow of diameter 14 cm located in both cambium and xylem at 14.5 cm depth

Furthermore, the four-point electrical resistivity technique implemented in this study is suitable for early detection of decay in living trees where resistivity decreases significantly with decay. Additionally, wood decay and hollow at any location in a tree stem could be detected using this resistivity technique by probing different sides and the entire stem of the tree under inspection. Probing only one side of the tree stem would not give accurate and detailed information about the state of health of the whole stem. Also, detection points of the resistivity anomalies created by wood decay and hollows in a living tree, expressed in terms of the current electrode separation, may provide information on the extent of decay and cavities.

Conclusion

A study on the early detection of the location and extent of wood decay and hollows in living almond trees (*Terminalia catappa* L. Roxb.) using the four-point electrical resistivity technique has been presented. Field results confirmed a steep rise in resistivity values from cambium to xylem of healthy almond trees—a general characteristic of healthy hardwood trees. Results also showed that decayed almond trees have a resistivity that is significantly lower than those of healthy trees, whilst hollowed almond trees have a resistivity that is notably higher than those of healthy trees. The resistivity method was able to detect the presence and location of the resistivity anomalies produced by modelled wood decay and hollows in the laboratory prototype. Wood decay and hollows in living almond trees could be detected by matching the resistivity profiles of the trees under investigation with the resistivity profiles of the laboratory prototype with modelled decay and hollows. The method indicated that stems of the randomly selected living almond trees were mostly healthy at the time of measurements.

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