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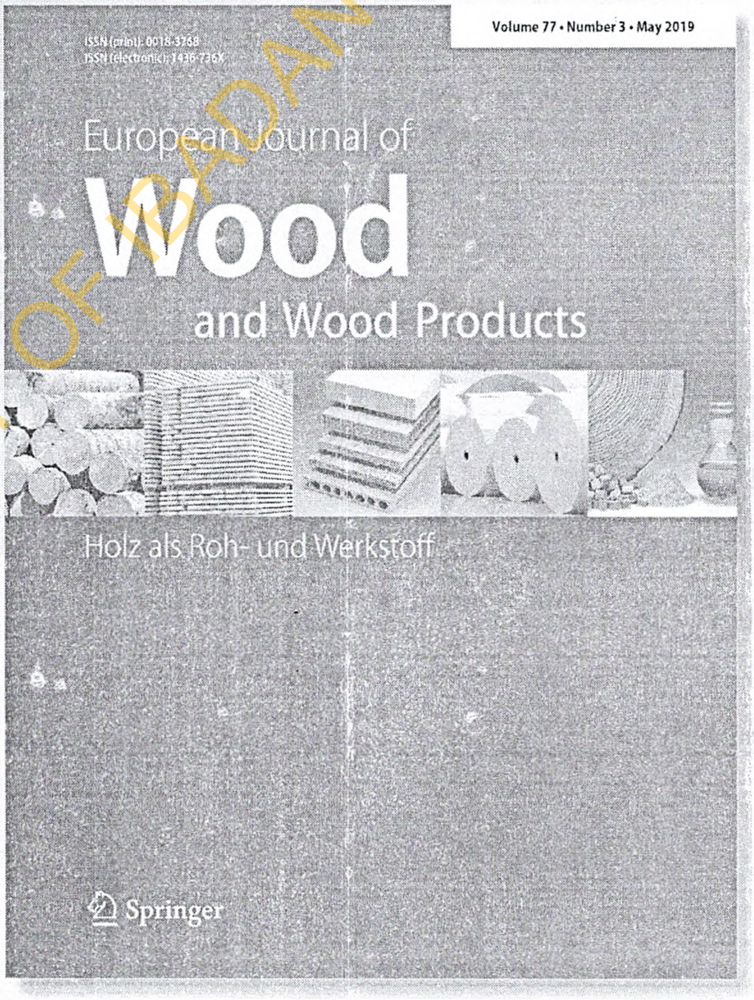

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ORIGINAL

A four-point electrical resistivity method for detecting wood decay and hollows in living trees

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Abstract

An accurate method of detecting wood decay and hollows or cavities in living trees is useful for risk assessment and maintenance of both forest and urban trees. This study presents the implementation of the four-point electrical resistivity method for the early detection of the presence, location and extent of wood decay and hollows in living acacia trees (*Senna alata* L.). Electrical resistivity measurement of randomly selected living acacia trees and a freshly-cut acacia tree with decay and hollows were taken to obtain electrical resistivity profiles for sound, decayed and hollowed trees. A laboratory experiment was set up to replicate the resistivity profiles. Wood decay and hollows were replicated at different depths in the laboratory prototype using good electrical conductors and insulators respectively. Resistivity profiles for the sound, decayed and hollowed trees were obtained from the experimental and field results. The resistivity profiles were applied to detect decay and hollows of similar dimensions in living trees through resistivity curve matching. The electrical resistivity of the decayed acacia tree was markedly lowered by an average factor of 5 compared to that of the sound acacia tree. Likewise, the electrical resistivity of the hollowed acacia tree was noticeably greater than that of the sound acacia tree by an average factor of 4. Wood decay and hollows modelled into the laboratory prototype were detected with relatively lower and higher resistivity anomalies respectively. The method indicated that 80% of the randomly selected living trees were sound, healthy trees, whilst 20% had decay and hollow at the time of measurements. This method is suitable for early detection of decay and hollows in hardwood trees.

1 Introduction

Wood decay is the process by which wood is decomposed by micro-organisms to provide nutrients for their survival (Harris et al. 2004). It has been reported that wood decay within a tree trunk is a major cause of tree failure, which frequently leads to loss of human lives and colossal damage to property in urban areas (Johnstone et al. 2010). Besides, the economic value of a living tree is reduced significantly by wood decay since decayed wood would not attract the same market value as sound wood—wood decay causes a decrease in wood density (Beall and Wilcox 1987; Goncz et al. 2018). Additionally, the ecological value of a living tree in conserving the environment from the threat of climate change is significantly reduced by wood decay. Therefore, an accurate method of detecting decay in trees would be useful for risk assessment and maintenance of living trees both in the forest and urban settlement.

Electrical resistivity methods were originally designed and are commonly used for ground survey (Herman 2001; Reynolds 2011). However, their viability in detecting wood decay and hollows in living trees has been reported by researchers in various publications (Ostrofsky and Shortle 1989; Shortle 1990; Manyazawale and Ostrofsky 1992; Butin 1995; Rinn 1999; Martin and Günther 2013). The main 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

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increase and therefore electrical resistance would decrease (Shigo 1991; Goh et al. 2018).

According to Larsson et al. (2004), the invasion of the stem by wood decay fungi causes movement of water to the area of mycelia growth, thus mobilising metal ions released by damaged tree cell. This results in a decrease in the resistivity of the decayed tree compared with the sound tree (Shortle and Smith 1987; Goncz et al. 2018). A decrease in electrical resistance for bacterial wet wood was also reported by Nicolotti and Miglietta (1998). However, there are fungi in trees that lower electrical resistivity of the trees significantly without causing wood decay as reported by Kucera (1985).

The electrical resistivity methods are often called impedance methods. Electrical impedance tomography (EIT) determines the electrical conductivity within wood 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 of decay (Goncz et al. 2018).

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. Red heart—a visual defect in beech wood—was detected with a measured voltage drop of 1/3 to 1/5 of that measured on unaffected wood. However, the method was unable to reliably determine the extent of red heart in beech trees.

Larsson et al. (2004) implemented a four-point electrical resistivity (RISE) method to detect wood decay in living trees. Four-point measurements were made by passing a low-frequency alternating current to 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. The major drawback of the four-point electrical resistivity method is that it does not provide information on the volume or location of the decay (Larsson et al. 2004).

The aim of this study was to detect the presence, location and extent of the resistivity anomalies due to wood decay and hollows in living acacia tree stems (*Senna alata* L.) 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.

2 Materials and method

2.1 Field measurements

Electrical resistivity values of living trees were estimated using the four-point electrical resistivity method. Forty acacia trees (*S. alata* L.) of diameter ranging from 45 to 110 cm were randomly sampled from various locations on University of Ibadan campus, Ibadan, Nigeria. The random sampling of the trees was carried out between 1st May and 31st July 2014. 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 in centimetres (Reynolds 2011).

The implementation of the four-point electrical resistivity method involved the use of four electrodes, which were arranged across the length of the tree stem (Appendix 1 in Electronic Supplementary Material). 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 separations of 4 cm and 6 cm were used while varying the current electrodes positions by 2 cm 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

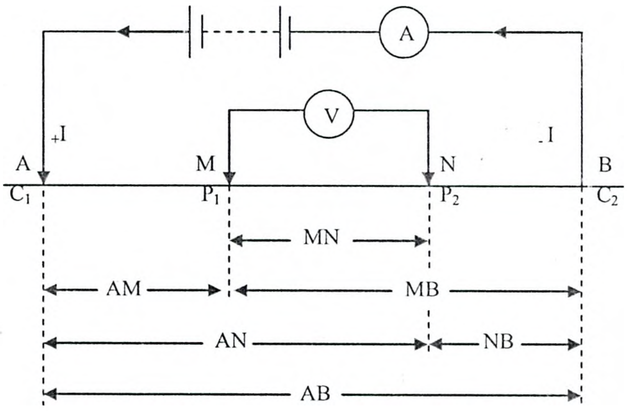

Fig. 1 Generalised form of electrode configuration in resistivity surveys. C_1 and C_2 are the current electrodes whilst P_1 and P_2 are the potential electrodes. MN, AM, MB, AN NB, and AB are the separations of the electrodes. AB is the current electrode separation whilst MN is the potential electrode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

separation, more of the injected current will flow into greater depths. The sort of electrode separations (Appendices 2 and 3 in Electronic Supplementary Material) used in this study requires the use of tiny electrodes to prevent a 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 locally fabricated for this research work to accommodate the small electrode separations. The electrode penetration depth in the tree was limited to 5 cm to prevent injury to the tree stem and fungi attack. 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).

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

where AM, MB, AN and NB are the separations of the electrodes as shown in Fig. 1 (Reynolds 2011). Further, the apparent resistivity values ρ_a were computed as

$$\rho_a = R_a K \qquad (2)$$

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

Electrical resistivity values of a log of acacia tree of stem diameter 40.5 cm and comprising decayed, hollowed and sound segments were also obtained. The tree was cut down after showing visual evidence of internal decay (Fig. 2). The resistivity measurement was taken on the log of wood, immediately after the tree was cut down, as it was done on living trees.

2.2 Laboratory measurements

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 sound acacia trees. This was carried out by modelling wood decay and hollows at different depths in a laboratory prototype, which serves as a sound 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 60 cm and diameter 50 cm and filled with compacted sawdust or wood dust, obtained from wood without decay or defects, to mimic stems of living trees. The stem perimeter of thickness 10 cm was modelled with compacted wet sawdust, whilst the stem centre of thickness 15 cm 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 subsection 2.1. The resistivity plot of the sound 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 the sound tree.

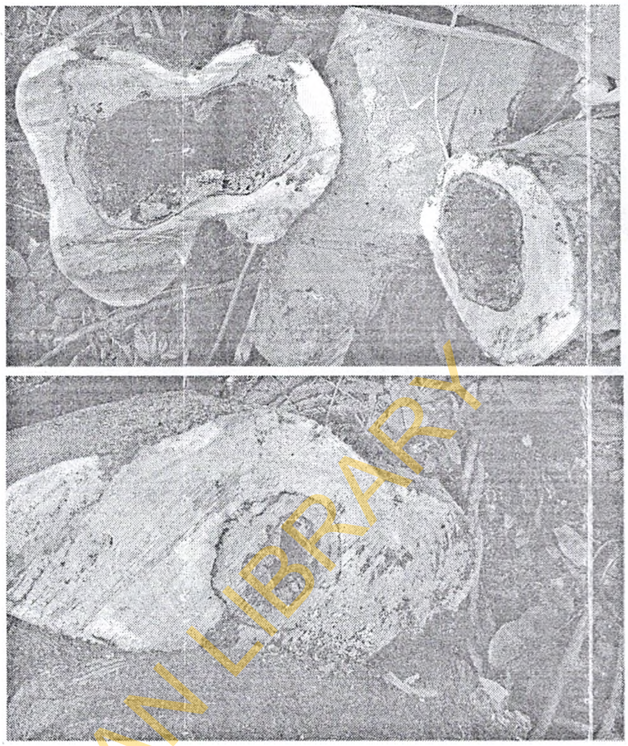

Fig. 2 Freshly-cut logs of decayed and hollowed acacia wood

Furthermore, the extent of wood decay or hollow was modelled into the laboratory prototype that serves as a replica for the sound tree. This was carried out by using good electrical conductors, for example, copper wire lumps (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 (Nicolotti et al. 2003; Goh et al. 2018). A copper wire lump of thickness 4 cm and length 20 cm was placed at 5-cm, 10-cm, 15-cm, and 20-cm depths, from the centre of the modelled decay to the laboratory prototype surface. Similarly, electrical insulators, for example, 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 6 cm and height 21 cm was modelled into the laboratory prototype at depths 4 cm, 12 cm, and 20 cm, 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.

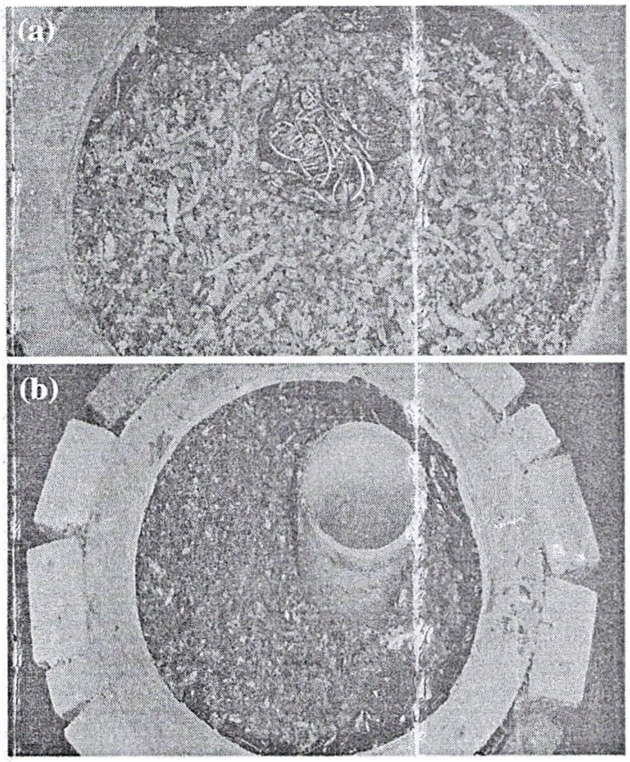

Fig. 3 A laboratory prototype with **a** a copper wire lump inserted to model wood decay, **b** a plastic cylinder inserted to model an hollow

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

A laboratory experiment was also carried out to determine the effects of tree decay and hollow size on the resistivity profile. Tree decay of various size was modelled into the laboratory prototype replicating a healthy acacia tree, using copper wire lumps of different thicknesses—5 cm, 8 cm and 12 cm, inserted at depths of 5 cm, 6.5 cm, and 8.5 cm from the centre of the wire lumps to the laboratory prototype surface, respectively. Hollows of different diameters—8 cm, 10 cm and 14 cm, were also modelled into the laboratory prototype at 4-cm, 5-cm, and 7-cm depths from the centre of the hollows to the laboratory surface, respectively. VES was carried out to detect both the presence and location of the resistivity anomalies created by the modelled wood decay and hollows.

3 Results

3.1 Resistivity values of sound acacia trees and their replica

Table 1 shows the resistivity values of four sound acacia 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 sound acacia trees show a major trend—a series of low resistivity values followed by a series of high resistivity values. The low resistivity values represent the stem perimeter of the tree whilst the high resistivity values correspond to the stem centre of the tree. The diameter of trees 1 and 2 is 54.5 cm whilst that of trees 3 and 4 is 50.4 cm. Figure 4 shows that the resistivity profiles of the acacia trees and that of the laboratory prototype are identical. The resistivity values of all the forty

Table 1 Resistivity values of four acacia trees with similar diameter

AB/2[a] (cm)	MN[b] (cm)	Resistivity (Ωm)					
		Tree 1	Tree 2	Tree 3	Tree 4	Mean value	Laboratory prototype
4	4	46.276	61.167	50.611	60.790	54.711	45.427
6	4	40.464	70.120	61.575	77.409	62.392	61.827
8	4	46.464	70.686	56.549	73.513	61.803	63.146
10	4	44.636	68.009	52.176	70.874	58.924	79.922
12	4	1847.256	2704.911	1880.243	2759.889	2298.075	1140.513
14	4	1854.796	2774.655	1915.115	2789.734	2333.575	1508.170
16	6	2988.597	4077.159	3265.686	3443.814	3443.814	2100.638
18	6	3116.460	4046.371	3116.460	4448.495	3681.947	3040.484
20	6	3265.686	4167.637	3029.312	4665.265	3781.975	3296.128
22	6	3502.247	4109.203	3113.947	4787.787	3878.296	3473.620
24	6	3683.832	4191.482	3153.719	4986.650	4003.921	3890.250
26	6	3873.961	4338.414	3277.561	5256.764	4186.675	4061.485

[a] Current electrode half separation

[b] Potential electrode separation

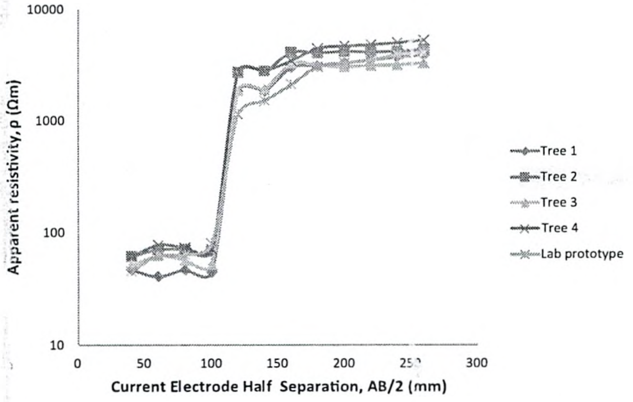

Fig. 4 Resistivity plots of acacia trees of similar diameter and their replica

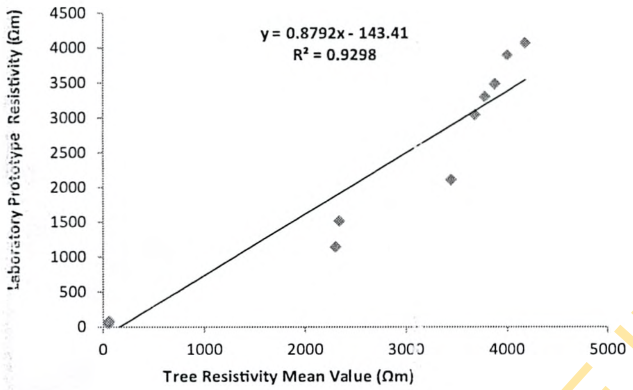

Fig. 5 Resistivity of laboratory prototype versus mean resistivity of acacia trees

randomly selected acacia trees are presented in Appendix 4 in Electronic Supplementary Material.

Furthermore, the resistivity profiles of the sound acacia trees correlated strongly with that of the laboratory prototype replicating the sound trees ($r^2 = 0.9298$), as shown in Fig. 5. Therefore, the resistivity profile of the laboratory prototype was a true replica of the sound acacia trees of similar diameter.

Table 2 Resistivity values of a decayed-hollowed acacia tree

AB/2[a] (cm)	MN[b] (cm)	Resistivity (Ωm)			
		Sound tree segment		Decayed-hollowed segment	
		Side A	Side B	Side A	Side B
4	4	64.748	50.611	12.912	11.875
6	4	77.409	61.575	13.105	12.273
8	4	67.858	56.549	14.219	13.851
10	4	69.805	52.176	15.302	14.625
12	4	2144.137	1880.243	5621.488	5731.472
14	6	1990.513	1915.115	6032.421	6800.638
16	6	2968.805	3265.686	7889.668	5623.105
18	6	2940.531	3116.460	8606.318	6609.824
20	6	3041.753	3029.312	9591.880	7264.529
22	6	2997.079	3113.947	10,572.536	8314.141

[a] Current electrode half separation

[b] Potential electrode separation

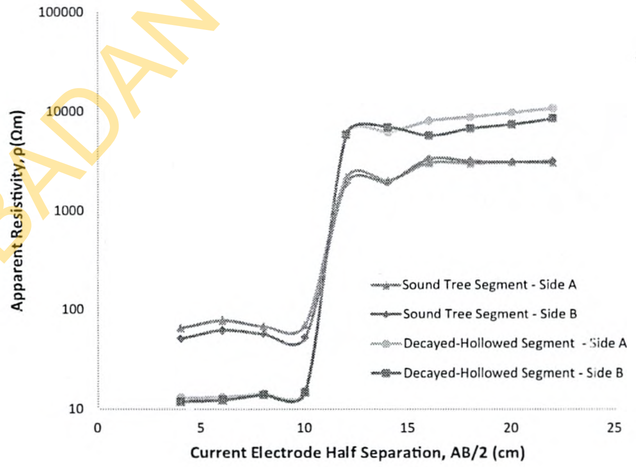

Fig. 6 Resistivity plots of a decayed-hollowed and sound segments of an acacia tree

3.2 Resistivity values of a decayed-hollowed acacia tree

Electrical resistivity values of a decayed-hollowed acacia tree of stem diameter 40.5 cm are presented in Table 2. The acacia tree comprised three sections—decayed, hollowed and sound segments. Table 2 shows the presence of wood decay in the stem perimeter of the acacia tree as represented by a series of lower resistivity values compared to those of the sound acacia tree. This trend is clearly displayed in Fig. 6 as a sharp decrease in resistivity values in the region of the resistivity plots corresponding to the stem perimeter. The resistivity values of the decayed stem-perimeter varied between 12 and 15 Ωm, whilst those of the sound stem-perimeter ranged between 51 and 77 Ωm. The length and diameter of the decayed section were 20 cm and 6 cm respectively. The sound tree segment is of stem diameter 40.5 cm and length 50 cm. Table 2 also shows the presence of a cavity or hollow in the stem centre of the acacia tree as represented by a series of higher resistivity values compared to those of the sound acacia tree. This is equally shown in Fig. 6 as a sharp increase in resistivity values in the stem centre section of the resistivity plots. The resistivity values of the hollowed stem-centre varied between 5622 and 10,573

Ωm, whilst those of the sound stem-centre ranged between 1880 and 3114 Ωm. The length and diameter of the hollowed segment were 28 cm and 14 cm, respectively.

3.3 Laboratory results

Table 3 comprises the electrical resistivity values of the laboratory prototype with a copper wire lump inserted at different depths to model tree decay, and which introduced anomaly into the resistivity profile of the prototype. The resistivity values of the laboratory prototype representing a sound 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 separations, AB/2, where the resistivity anomaly was detected, as shown in Table 4. For comparison, the resistivity values of the laboratory prototype representing a sound tree (i.e. without anomaly) are also included. Figure 7 shows the resistivity plots of the laboratory prototype with an anomaly (i.e. modelled tree decay) and without anomaly. The resistivity anomaly produced by the modelled tree decay

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] (cm)	MN[b] (cm)	Resistivity (Ωm)				
		5-cm depth	10-cm depth	15-cm depth	20-cm depth	No anomaly
4	4	11.214[c]	39.155	41.025	42.852	45.427
6	4	15.253[c]	57.111	56.294	57.209	61.827
8	4	17.388[c]	59.896	60.583	61.172	63.146
10	4	65.273	21.468[c]	76.192	77.105	79.922
12	4	910.275	296.186[c]	1012.621	1020.726	1140.513
14	4	1206.896	385.943[c]	1315.022	1321.165	1508.170
16	6	1853.310	1901.681	521.267[c]	1840.198	2100.638
18	6	2591.041	2652.175	752.139[c]	2605.429	3040.484
20	6	2907.586	2835.022	831.271[c]	2801.226	3296.128
22	6	3168.315	3214.334	3120.182	782.943[c]	3473.620
24	6	3497.220	3571.939	3563.142	886.752[c]	3890.250
26	6	3834.090	3953.136	3845.396	1010.031[c]	4061.485

[a] Current electrode half separation

[b] Potential electrode separation

[c] Detection point of the copper wire lump

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] (cm)	MN[b] (cm)	Resistivity (Ωm)			
		4-cm depth	12-cm depth	20-cm depth	No anomaly
4	4	155.139[c]	57.222	59.382	45.427
6	4	206.358[c]	73.901	76.701	61.827
8	4	215.219[c]	79.529	84.526	63.146
10	4	271.382[c]	93.018	98.711	79.922
12	4	1250.336	3546.251[c]	1251.728	1140.513
14	4	1629.765	4832.318[c]	1641.302	1508.170
16	6	2251.221	6935.102[c]	2280.119	2100.638
18	6	3152.032	10042.641[c]	3246.058	3040.484
20	6	3401.714	3412.927	10388.652[c]	3296.128
22	6	3587.352	3591.536	11215.716[c]	3473.620
24	6	4002.159	4002.172	12502.481[c]	3890.250
26	6	4179.172	4185.263	12995.004[c]	4061.485

[a] current electrode half separation

[b] Potential electrode separation

[c] Detection point of the modelled hollow

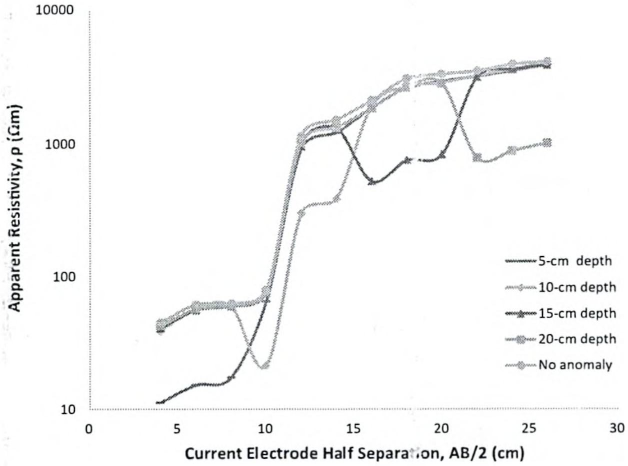

Fig. 7 Resistivity plots of the laboratory prototype with a copper wire lump at 5-cm, 10-cm, 15-cm, and 20-cm depths from the centre of the modelled decay to the surface of the laboratory prototype

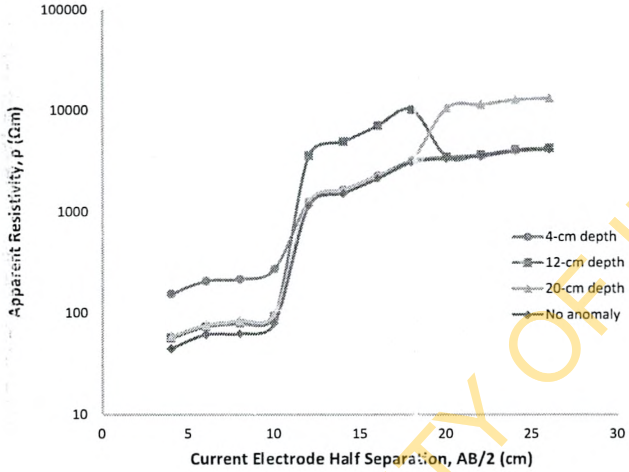

Fig. 8 Resistivity plots of the laboratory prototype with a modelled hollow at 4-cm, 12-cm, and 20-cm depths from the centre of the modelled hollow to the laboratory prototype surface

was detected as a mismatch in the resistivity profiles caused by a sharp decrease in resistivity values at the location of the copper wire (Fig. 7). Moreover, the corresponding current electrode half separations, AB/2, constitute detection points of the anomaly (or modelled tree decay). Additionally, the hollow modelled in the laboratory prototype at various depths resulted in very high resistivity values recorded at the detection points of the anomaly as presented in Table 4 and graphically in Fig. 8.

The results of the experiment carried out on the effect of the size of decay and hollow on the resistivity profiles are presented in Tables 5 and 6, respectively, and graphically in Figs. 9 and 10. The results showed that the extent of decrease or increase in resistivity values depends on the thickness of the copper wire lump or the diameter of the hollow respectively. Table 5 and Fig. 9 show that the largest decrease in resistivity values of an average factor 6.4 was observed for 12-cm thick copper wire lump placed at 8.5-cm depth, with the centre of the wire as the reference point; followed by 8-cm thick copper wire lump, placed at 6.5-cm depth, with an average factor of 5.1; and the lowest decrease was observed for 5-cm thick copper wire lump, placed at 5-cm depth, with an average factor of 3.8. Likewise for the hollow, Table 6 and Fig. 10 show that the largest increase in resistivity values of an average factor 5.6 was observed for 14-cm hollow diameter placed at 7-cm depth, with the centre of the hollow as the reference point; followed by 10-cm hollow diameter with an average factor of 4.0, placed at 5-cm depth; and the lowest increase was observed for 8-cm hollow diameter with an average factor of 3.1, placed at 4-cm depth. The experimental results also showed that as the conducting medium and hollow increase in size, the detection points of the anomalies also widen.

3.4 Discussion

In this study, a steep rise in electrical resistivity values from the stem perimeter to the stem centre was observed as shown in Fig. 4. This trend was equally reported by Bieker and Rust (2010), who estimated sapwood and heartwood width in Scots pine (*Pinus sylvestris* L.) trees in lower Saxony, Germany, 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 sound 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). Thus, the steep rise in electrical resistivity values from the stem perimeter to the stem centre implied that the acacia trees presented in Fig. 4 were healthy sound trees.

The in-situ measurement of the resistivity values of freshly-cut acacia trees with decay and hollow showed that decay causes a significant decrease in the resistivity values of a sound 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 (Smith and Shortle 1988). Additionally, Larsson et al. (2004) reported that cavities or hollows increase stem resistivity because they do not conduct electricity.

Table 5 Resistivity values of the laboratory prototype with copper wire lumps of length 15 cm and of different thicknesses

AB/2[a] (cm)	MN[b] (cm)	Resistivity (Ωm)			
		Thickness: 5 cm	8 cm	12 cm	Without anomaly
4	4	23.192[c]	16.018[c]	12.521[c]	81.336
6	4	31.837[c]	25.259[c]	20.398[c]	128.032
8	4	34.011[c]	26.713[c]	21.526[c]	135.201
10	4	130.528	28.164[c]	22.073[c]	142.439
12	4	142.916	139.825	23.641[c]	153.150
14	4	155.281	150.692	141.058	162.320
16	6	241.389	238.213	230.629	249.380
18	6	5530.211	5500.964	5452.122	5825.692
20	6	5890.813	5872.158	5831.806	6157.670
22	6	6136.079	6119.172	6080.514	6425.308
24	6	6293.512	6280.361	6235.119	6577.804
26	6	6520.758	6505.019	6461.682	6816.513

[a] Current electrode half separation

[b] Potential electrode separation

[c] Detection point of the copper wire lump

Table 6 Resistivity values of the laboratory prototype with hollows of length 21 cm and of different diameters

AB/2[a] (cm)	MN[b] (cm)	Resistivity (Ωm)			
		Diameter: 8 cm	10 cm	14 cm	Without anomaly
4	4	250.217[c]	327.913[c]	458.174[c]	81.336
6	4	392.944[c]	516.286[c]	719.634[c]	128.032
8	4	413.528[c]	545.925[c]	753.211[c]	135.201
10	4	432.016[c]	578.782[c]	797.735[c]	142.439
12	4	195.592	618.011[c]	855.159[c]	153.150
14	4	201.127	226.825	914.052[c]	162.320
16	6	276.152	299.672	335.821	249.380
18	6	5938.371	5976.521	6080.913	5825.692
20	6	6264.892	6315.243	6420.285	6157.670
22	6	6531.533	6598.726	6697.019	6425.308
24	6	6698.219	6748.119	6851.725	6577.804
26	6	6929.047	6985.038	7095.814	6816.513

[a] Current electrode half separation

[b] Potential electrode separation

[c] Detection point of the modelled hollow

The electrical resistivity values of the decayed acacia tree were considerably decreased by an average factor of 5 in comparison to those of the sound acacia tree. Likewise, the electrical resistivity values of the hollowed acacia tree were noticeably greater than those of the sound acacia tree by an average factor of 4. This result is similar to that reported by Larsson et al. (2004), who indicated that Norway spruce trees with decay had a resistivity lowered by a factor of 2 compared to sound trees.

The depths of placement of the modelled tree decay and hollow in the laboratory prototype can be matched with the detection points AB/2. This would be useful for determining the location of tree decay and hollows with similar resistivity anomalies given the detection points of the anomalies. 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).

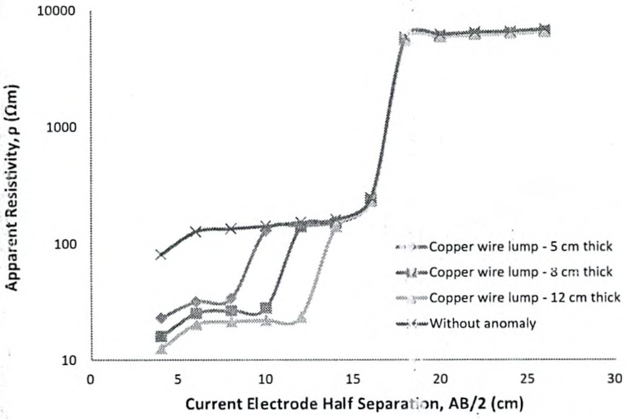

Fig. 9 Resistivity plots of the laboratory prototype with copper wire lumps (replicating wood decay) of thicknesses 5 cm, 8 cm and 12 cm inserted at 5-cm, 6.5-cm, and 8.5-cm depths respectively from the centre of the wire lump to the laboratory prototype surface

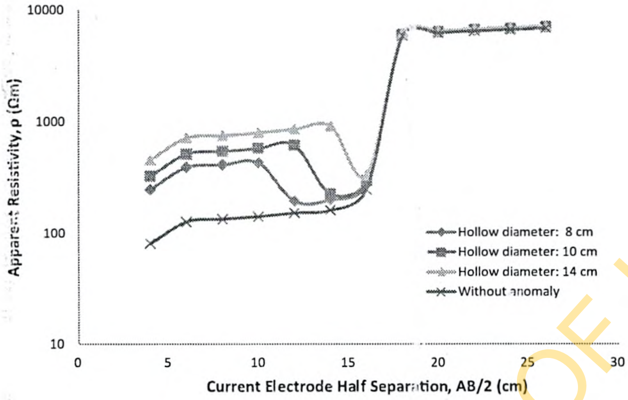

Fig. 10 Resistivity plots of the laboratory prototype with hollow of diameters 8 cm, 10 cm and 14 cm inserted at 4-cm, 5-cm, and 7-cm depths respectively from the centre of the hollow to the laboratory prototype surface

4 Conclusion

This study demonstrated the application of the four-point electrical resistivity technique for the early detection of the presence, location and extent of wood decay and hollows in living acacia trees. Field results confirmed a steep rise in resistivity values from stem perimeter to stem centre of healthy acacia trees. The resistivity values of decayed acacia trees were lower by a factor of 5 than those of sound acacia trees. Similarly, the resistivity values of hollowed acacia trees were higher by a factor of 4 than those of sound acacia trees. The results of the laboratory experiment showed that 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. There was a strong agreement between the field results and the laboratory results. Hence, the resistivity profiles of the laboratory prototype with modelled wood decay and hollows serve as a sort of benchmark for the early detection of the presence, location and extent of decay and hollows of similar dimension in living acacia trees. Wood decay and hollows in living trees could be detected by matching the resistivity profiles of the trees under investigation with those of the laboratory prototype with modelled decay and hollows. However, there are fungi activities in wood causing a notable reduction in electrical resistivity values of trees without resulting in decay. This constitutes a limitation to the use of electrical resistivity values exclusively for detecting wood decay in trees. In addition, seasonal changes and all other factors influencing the moisture content of the living tree have an impact on the results of the resistivity measurements and thus, should be considered especially when evaluating absolute values and not only relative changes.

References

Beall F, Wilcox W (1987) Relationship of acoustic emission during radial compression to mass loss from decay. For Prod J 37:38–42

Bieker D, Rust S (2010) Non-destructive estimation of sapwood and heartwood width in Scots pine (*Pinus sylvestris* L.). Silva Fennica 44(2):267–273

Brazee NJ, Marra RE, Göcke L, Wassenaer PV (2010) Non-destructive assessment of internal decay in three hardwood species of northeastern North America using sonic and electrical impedance tomography. Forestry Adv. Access, Oxford

Butin H (1995) Tree diseases and disorders: causes, biology, and control in forest and amenity trees. Oxford University Press, Oxford, p 262

Goh CL, Rahim RA, Rahiman MHF, Talib MTM, Tee ZC (2018) Sensing wood decay in standing trees: a review. Sens Actuators A 269:276–282

Goncz B, Divos F, Bejo L (2018) Detecting the presence of red heart in beech (*Fagus sylvatica*) using electrical voltage and resistance measurements. Eur J Wood Prod 76(2):679–686

Guyot A, Ostergaard KT, Lenkopane M, Fan J, Lockington DA (2013) Using electrical resistivity tomography to differentiate sapwood from heartwood: application to conifers. Tree Physiol 33:187–194

Harris RW, Clark JR, Matheny NP (2004) Arboriculture: integrated management of landscape trees, shrubs, and vines, 4th edn. Prentice Hall, New Jersey

Herman R (2001) An introduction to electrical resistivity in geophysics. Am J Phys 69(9):943–952

Johnstone D, Moore G, Tausz M, Nicolas M (2010) The measurement of wood decay in landscape trees. Arboric Urban For 36(3):121–127

Kucera LJ (1985) Kernspintomographie und elektrische Widerstandsmessung als Diagnosemethoden der Vitalität erkrankter Bäume. Schweizerische Zeitschrift für Forstwesen (Magnetic resonance tomography and electrical resistance measurement as diagnostic methods of the disease-affected trees. Swiss J For 137(8):673–690 **(in German)**

Larsson B, Bengtsson B, Gustafsson M (2004) Nondestructive detection of decay in tree. Tree physiol 24:853–858

Manyazawale B, Ostrofsky WD (1992) An assessment of internal decay of red spruce (picea rubenssarg.) using the shigometer. Maine Agricultural Experiment Station Miscellaneous Report 369

Martin T, Günther T (2013) Complex resistivity tomography (CRT) for fungus detection on standing trees. Eur J Forest Res 132(5–6):765–776

Nicolotti G, Miglietta P (1998) Using high-technology instruments to assess defects in trees. J Arboric 24:297–302

Nicolotti G, Socco LV, Martinis R, Godio A, Sambuelli L (2003) Application and Comparison of three tomographic techniques for the detection of decay in trees. *J* Arboric 29:66–78

Ostrofsky WD, Shortle WC (1989) Application of the shigometer for assessing tree and forest health and wood product quality. Rev Trop Plant Pathol 6:39–57

Reynolds JM (2011) An introduction to applied and environmental geophysics, second edn. Wiley-Blackwell, London

Rinn F (1999) Device for Investigation Materials. US-Patent US6813948; International Patent. PCT/DE00/01467 (1999.05.11). Basic Patent Describing Sonic and Electrical Resistivity Tomographies

Shigo AL (1991) Modern arboriculture. Shigo & Trees, New Hampshire, p 421

Shortle WC (1990) Ionization of wood during previsual stages of wood decay. Biodeterior Res 3:333–348

Shortle WC, Smith KT (1987) Electrical properties and rate of decay in spruce and firwood. Phytopathology 77:811–814

Smith KT, Shortle WC (1988) Electrical resistance and wood decay by white rot fungi. Mycologia 80:124–126