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2002

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Citation for published version (APA):

Larsson, B., Bengtsson, B. A., & Gustafsson, M. (2002). *Non Destructive Detection of Decay in Living Trees*. (Technical Report LUTEDX/(TEAT-7111)/1-15/(2002); Vol. TEAT-7111). [Publisher information missing].

Total number of authors:

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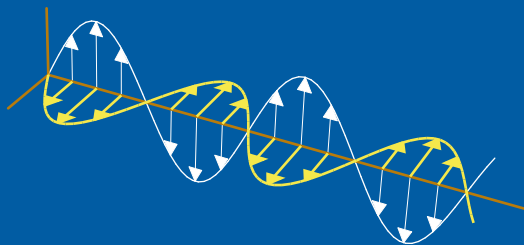
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Non Destructive Detection of Decay in Living Trees

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Editor: Gerhard Kristensson

© Bertil Larsson *et al.*, Lund, September 23, 2002

Abstract

It is shown that four point resistivity measurements can be used to detect decay in living trees. A low frequency alternating current is injected into the trunk and the induced voltage is measured between two points along the trunk. With additional measurement of the cross section area, the effective resistivity of the trunk is estimated. A comparison within a group of trees shows that trees in decay have approximately a factor of two lower effective resistivity than sound trees. The method is tested on several different groups of spruce (*Picea abies*); in total more than 300 trees are examined. The tests show that the method can detect decay caused by *Heterobasidion annosum* with high accuracy. Finite element modeling and simulations are used to validate the method.

1 Introduction

A large percentage of the harvested trees has some kind of decay that makes them useless from an economical point of view. The timber are left for destruction or at best used for heating. In the year 2001, the average waste in Sweden was 15% of the harvest, corresponding to a yearly loss of 1 billion SEK (US\$100 million) [6]. The need for an accurate method to detect decay in living trees is therefore obvious. The detection of decay in living trees is done at two different stages. The first is in the highly mechanized harvesting process, and the second is at the validation of estates marked for sale or in in fragile environments, *i.e.*, parks. The method described here can be used for both tasks and only the physical appearance of the measuring device has to be designed differently.

Wood decay is caused by specialized fungi [5]. The infection of fungi spores occur mostly at root level. Damage of the root system caused by heavy vehicles or animals inflict a small injury on the roots and thereby opens the protective shield of the bark. The infection can also spread via the root system from a nearby tree. As the fungi grows from the root and up, it makes its environment pleasant. Lots of water is found at the front of growth. Here, the fungi is active and consumes the cell structure, releasing metal ions in particular potassium [9]. Behind this active upward moving front there is an area of wasted wood lacking the supporting cell structure. Decayed wood can be characterized by a change of: color, odor, moisture-holding capacity, dimensions, density, and mechanical properties [12].

In this paper, it is shown that a simple four-point measurement can be used to detect decay by estimation of the effective resistivity in the trunk, *i.e.*, the RISE¹ method [2]. The effective resistivity is obtained from measurements of the induced voltage between two points along the trunk when a low frequency alternating current is fed into the trunk. The quotient between the voltage and the current times the cross-section area gives an approximation of the effective resistivity. Decay can be detected by comparison of the effective resistivity within a group of trees measured under similar conditions, *i.e.*, temperature, humidity, site conditions, and

¹RISE=Relative Impedance in Situ Examination

time of year. This comparison is quantified by the quotient between the effective resistivity and the effective resistivity of sound trees, *i.e.*, the relative resistivity. The relative resistivity of a tree with decay is typically a factor of two lower than the corresponding value of a sound tree. Several measurement campaigns have been performed to validate the method. In total more than 300 spruces have been examined. The method is shown to be very accurate to detect decay in the form of soft and hard rot and it is also possible to detect discolored wood.

Decay caused by two different types of fungi have been investigated: *Heterobasidion annosum* and *Armillaria mellea* [1, 5, 15]. *H. annosum* has the by far most economic impact as it penetrates the center of the trunk sometimes up to a height of ten meters. Fortunately, this type of decay is the easiest one to detect. The *A. mellea* is of little economic importance, although correctly measured it can be detected. The decay from this type is rarely spread above a half meter from the ground level. The vast majority of our measurements are made on spruces having decay from *H. annosum*.

There have been a few prior attempts to use electric methods to detect decay in living trees. The Shigometer is a method to measure the resistance of wood [5, 9, 16]. A small hole is made from the surface towards the center. Then a fork with two electrodes slides from the center and out. The horns of the fork measures the resistance of the surrounding tree and the decay is detected as a change of resistance. The drawback of this method is that the hole exposes the tree to spores after the measurement. The time of making a measurement is also long. Another electric method is impedance tomography, that can be used to show the location of the decay [19]. The measurements are time consuming and requires a larger number of sensors which makes the method less attractive. There are also various methods based on, *e.g.*, gamma radiation [8], X-ray radiation [7], microwave scanner [10], and magnetic resonance imaging [11]. Acoustical methods can also be used to detect decay [1, 4, 18, 20]. An overview on nondestructive methods is found in the proceedings from the International Symposium on Nondestructive Testing of Wood, *e.g.*, [13].

The organization of this paper is as follows. In Section 2, the RISE method is described. Experimental results are presented in Section 3. An electric model of decay in trees and FEM simulations are presented in Section 4. The results are discussed in Section 5.

2 Decay and the RISE method

The electrical properties of a tree change with the decay. As the fungi consumes the cell structure, metal ions, in particular potassium [9] are released. These ions are mobile in the humid front of the decay. The cone shaped decay thereby obtains a much lower resistivity. The RISE method utilizes this reduced resistivity in the humid front layer and humid rot, to detect decay by measurement of the effective resistivity of the trunk.

The effective resistivity is defined as the resistance of a piece of the trunk, ap-

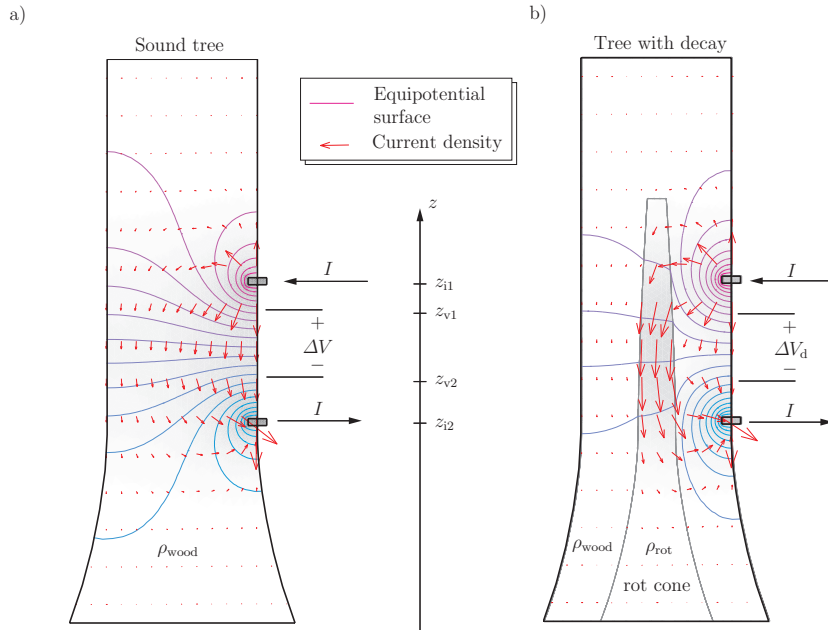


Figure 1: Illustration of the four point measurement. The sound tree, a), gives a higher voltage difference than the tree with decay, b), *i.e.*, $\Delta V > \Delta V_d$. The current is injected at height z_{i1} and exits at z_{i2} . The resistivity is determined from the voltage difference between z_{v1} and z_{v2} .

proximated to a cylinder with known height divided by the length and multiplied by the area of the cylinder. A fixed current is driven vertically through the trunk and the voltage is measured at two points on the surface of the trunk. The voltage difference ΔV , the current I , the distance between the measuring points l , and the cross section area A give the effective resistivity ρ . The relative resistivity ρ_r is defined by the resistivity divided by the average resistivity of the (assumed) sound trees $\langle \rho_{\text{sound}} \rangle$, *i.e.*,

$$\rho = \frac{\Delta V A}{I l} \quad \text{and} \quad \rho_r = \frac{\rho}{\langle \rho_{\text{sound}} \rangle}. \quad (2.1)$$

It is known that the effective resistivity of wood depends on the moisture content and the temperature [12, 17]. This makes it difficult to use the resistivity of an individual tree for the detection of decay. Instead the resistivity is compared within a group of trees measured under similar conditions. The relative resistivity is normalized to values around one for a group of sound trees.

The proposed method is an evaluation of the four-point resistance measuring method [14]. Four-point measurements are done by forcing a current through an object using one pair of electrodes, while measuring the voltage difference with another pair of electrodes, see Figure 1. A sound tree (left) gives a higher voltage difference than one with decay (right). The low resistivity of decay at the center results in a lower voltage difference. The resistance normalized with the cross section area will render an absolute value of the resistivity, that is related to the amount of decay. The benefit of this method compared to a two-point measurement is that

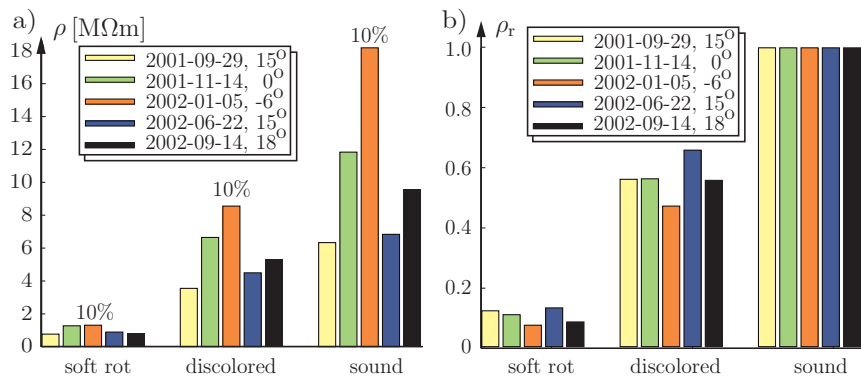


Figure 2: a) Comparison between the resistivity for three spruces at Romeleåsen, Scania, Sweden. The values were gathered at five occasions from September 2001 to September 2002. The dates and temperature are given in the legend. Observe that the values from 020105 are scaled to 10% to fit in the graph. b) The corresponding relative resistivity values. Core drilling classified the trees as affected by soft rot, discolored, and sound.

there is neither a degrading effect from the resistance of the current cables nor from the contact resistance at the feeding points. The latter is the major advantage. From simulations it is seen that the high current density at the injection points distorts the current density and produces unreliable measurements near the feeding points, see Section 4 and Figures 8–9.

A reference electrode is placed between the voltage measuring electrodes in order to get a noise free voltage reading. The voltage contact pins are thin needles but can be any contact surface, since the current flowing in the voltage sensors is low. The current is a low frequency alternating current, for the moment at 300 Hz, but higher frequencies are investigated for the purpose of using a capacitive sensor and/or to achieve more accurate information. The alternating current is signal processed in order to eliminate the disturbance caused by the galvanic elements that appear between the metal pins and the electrolytic sap.

3 Measurement results

Several measurement campaigns have been performed to evaluate the reliability of the method. From the measurements it is observed that the resistivity depends on time of year, type of tree, temperature, and humidity. Therefore one can not sample only one tree and from this predict the amount of decay. A more reliable method is to measure a significant group of trees and compare resistivity of the trees within the group. As an example, the resistivity of three spruces are shown in Figure 2a. The measurements were performed between September 2001 and September 2002. Core drill samples were used to classify the trees in the three groups; soft rot, discolored, and sound. Observe that the resistivity of the soft rot tree from 2002-01-05 (January 5, 2002) is higher than the resistivity of the sound tree from the other dates. The

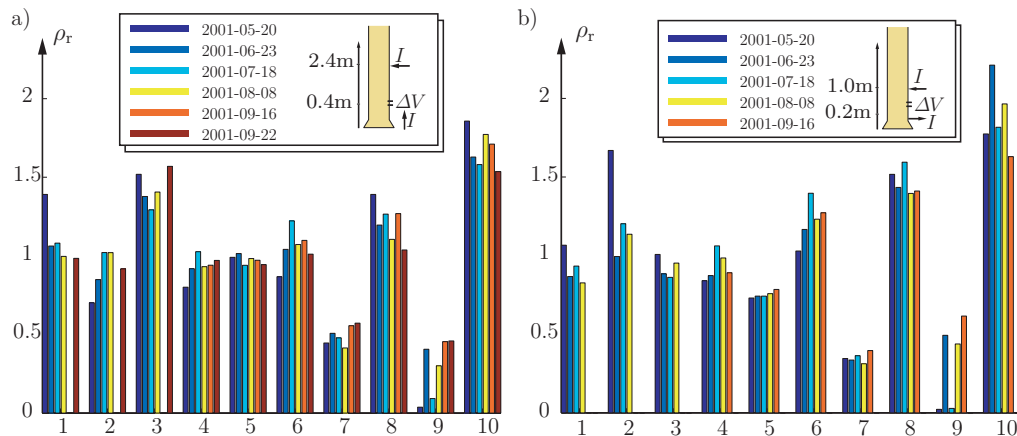


Figure 3: Comparison between the relative resistivity for ten spruces at Romeleåsen, Scania, Sweden. The values are gathered at six occasions from May to September 2001, see the legend. The values for trees 1,2,3 at 2001-09-16 are not available due to bad weather. The corresponding photos of the trunk cross section are depicted in Figure 4. a) The standard RISE measurement with the current is injected at a height between 2.3 m to 2.6 m and exits through the earth. b) RISE measurement with 80 cm between the feeding points.

high values at 2002-01-05 are probably due to the low temperature (-6°) during and before the measurement. The dependence on time of year and temperature is reduced by comparison of a relative resistivity, as seen in Figure 2b.

In Figure 3, the relative resistivity for ten spruces at Romeleåsen, Scania, Sweden are shown. The values were measured at six occasions from May to September 2001. Although the variation is not negligible, the pattern is clear. Trees number 7 and 9 have substantially lower values. After felling at October 23, 2001, photos of the fell cuts were taken, see Figure 4. Color zones and soft rot are clearly visible for trees number 7 and 9, respectively.

Two different measurement configurations are also compared in Figure 3. In Figure 3a, the standard measurement is used. In this case the current is injected at a height between 2.3 m to 2.6 m and exits through the ground. The voltage is measured between two points above and below the fell cut (approximately 20–50 cm above ground) and separated by 10 cm. In Figure 3b, the height of the measurement equipment is reduced to 80 cm. The voltage is again measured between two points separated 10 cm but now in the middle of the feeding points. The results are similar for the two measurement configurations.

It is known that *H. annosum* typically spreads from the root and up the trunk [5, Chap. 7]. This gives a decay in its final form (soft rot) close to the earth and early form (color zones) higher up the trunk. The RISE method can also be used to determine this spreading of decay in the trunk. In Figure 5, the current is fed into the trunk at height 4.4 m and exits through the earth. The resistivities are measured at the height 0.1 m, 1.0 m, and 2.0 m. The measurements are repeated for the directions north, west, south, and east. As observed from the values in comparison with the

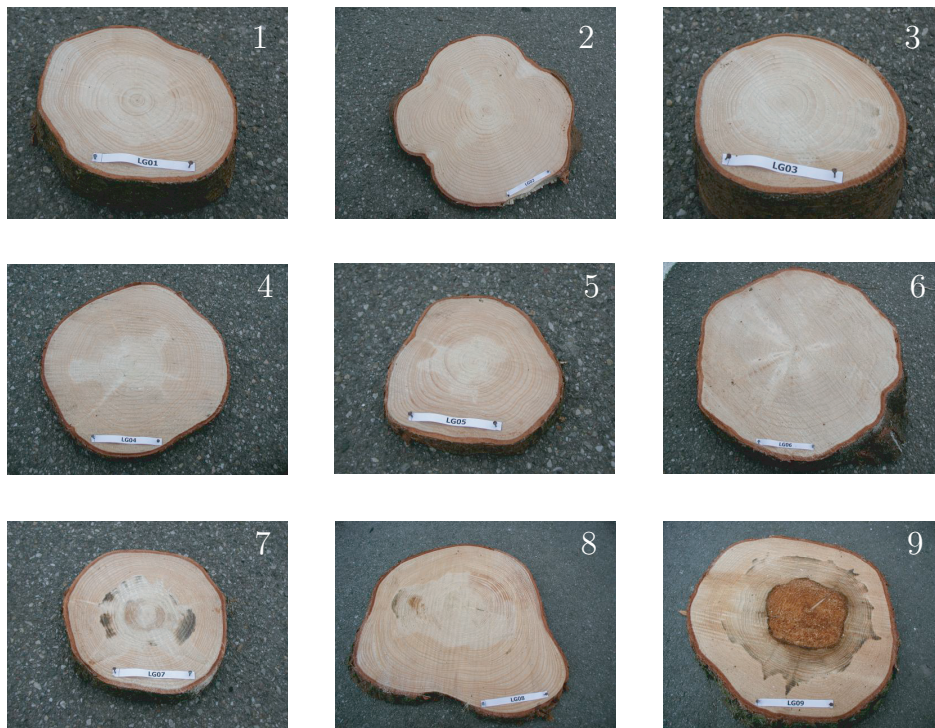


Figure 4: Photos of the trunk cross section for the trees in Figure 3. The trees were felled in October, 2001. Photos 1-6 and 8 show sound trees. Tree number 7 has color zones and tree number 9 has a region with soft rot. Tree number 10 is sound but not depicted.

cross section photos, the RISE method only gives information about the location of the decay in the vertical direction. This is mainly due to the dominating vertical direction of the current and hence equipotential surfaces in the horizontal plane. Horizontal resolution can be obtained with impedance tomography [19].

The RISE method gives a relative comparison between trees in a group consisting of similar trees. To be able to classify the trees as either sound, discolored, or affected by rot, it is necessary to have a sufficiently large group of sound trees. In this case the sound and affected trees have a relative resistivity around 1 and 0.5, respectively, see Figure 3. The average resistivity depends on the composition of sound and affected trees in the group, *e.g.*, the values are higher if the group has a large amount of affected trees. To reduce the coupling between the relative resistivity and the composition of the group, the resistivity is normalized with respect to the average resistivity of the assumed sound trees.

In Figure 6, a histogram of the relative resistivity and the amount of decay for a measurement campaign containing 87 spruces in Klosterheden, Jylland, Denmark is shown [3]. The trees were from two different groups. One group of 67 trees were 42 years old and had an average diameter of 18.6 cm. The other group were 90 years old with an average diameter of 24.3 cm. After felling, the trees were classified as either sound, discolored, greatly discolored, less than 1/3 rot, or more than 1/3 rot [3]. Since the histogram contains two different groups of trees the resistivities were first

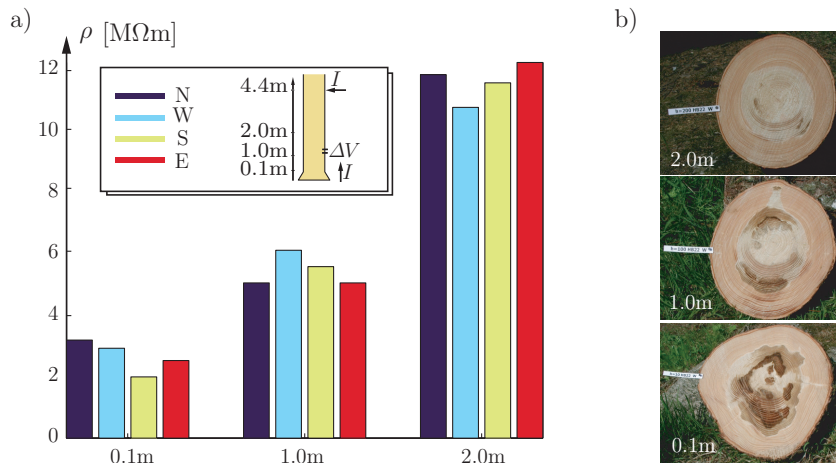


Figure 5: a) The resistivity of an infected spruce at the height 0.1 m, 1.0 m, and 2.0 m. The current were fed at the height 4.4 m and through the ground. b) The corresponding photos of the trunk cross section.

normalized with respect to the average resistivity value of the assumed sound trees in each group. Here, the simple diagnostic of resistivity values above average was used to pick the sound trees. The trees were then grouped into bins of the size 0.04 to give the histogram in Figure 6.

In total around 300 spruces have been examined with the RISE method between 1999 and 2002. In Figure 7, a histogram of 267 trees from 11 measurement campaigns is shown, see also Table 1. The relative resistivities were normalized and gathered as in the previous example. The classification was done by examination of photos showing the fell cut or by core drill samples. The trees that were not felled or checked by drill samples were classified as unknown. Even though several groups of trees were gathered in histogram and the normalization was performed in a very simple fashion, the general trend of the histogram is clear. Low values 0–0.4 correspond to soft rot or greatly discolored trees. Values over 0.8 correspond to sound or discolored trees. Values between 0.4 and 0.8 are less clear, here there are both soft rot, discolored and sound trees. It is also worth to observe that the subjective classification from the photos is a major source of error. The soft rot tree with relative resistivity around 1 is not due to a miss classification. However, manual inspection of the tree would have shown that the tree was damaged and hence called for an alternative inspection. The high value of this tree is probably due to drought.

4 Electrical modeling

To enhance the understanding of the RISE method, the Finite Element Method (FEM) is used. For a tree with given geometry, resistivity, and measurement setup, the FEM is used to determined the induced voltage from an injected current and hence the resistivity. The sound tree is modeled as a cylindrical trunk with a conical root. Both the trunk and the root is assumed to have the resistivity ρ_{wood} . The

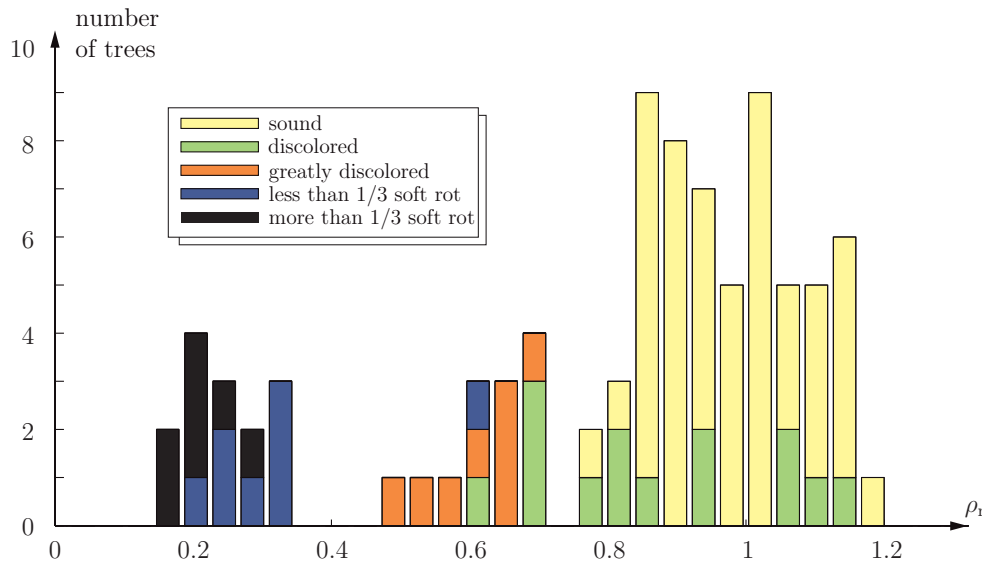


Figure 6: Comparison between the relative resistivity and the amount of decay for 67 + 20 spruces in Jylland, Denmark [3]. The trunks were classified as either sound, discolored, greatly discolored, less than 1/3 rot, or more than 1/3 rot.

affected part of the tree is modeled with two cones. The inner cone constitutes the soft rot part. It has the resistivity ρ_{rot} and it is surrounded by the humid front layer with resistivity ρ_{front} , see also [5, Chap. 7]. The resistivity in wood is in general anisotropic, *i.e.*, the resistivity depends on directions [12, 17]. To get a basic understanding of how the resistivity depends on the measurement setup, the simplified case with isotropic resistivity and the front layer resistivity $\rho_{\text{front}} = \rho_{\text{rot}}$ is analyzed. The current is injected into the trunk at z_{i1} and exits at z_{i2} , see Figure 1.

A parametric study is performed to analyze how the voltage distribution along the trunk depends on the shape of the affected part and the contrast between the resistivity in the affected part and the resistivity in the trunk. From the FEM simulations it is concluded that the voltage depends weakly on the root shape. In the following, a root cone with radius $r_r = 1.2r_t$ and height $z_r = 0.8r_t$ is used.

In Figure 8, it is observed that the potential changes rapidly close to the current feed points. The potential drops from its highest value at the injection point to its lowest value at the exit point. Away from the connection points the potential change is less drastic and, hence, it is possible to relate the potential distribution on the surface of the trunk to the effective resistivity inside the trunk. The effective trunk resistivity $\rho_h = \rho_h(z)$ is obtained by homogenization of the resistivity in the trunk, *i.e.*, a parallel connection. It is given by

$$\frac{A}{\rho_h(z)} = \frac{A_{\text{rot}}(z)}{\rho_{\text{rot}}} + \frac{A - A_{\text{rot}}(z)}{\rho_{\text{wood}}} \quad (4.1)$$

where A_{rot} and A are the cross section areas of the rot region and the trunk, respectively. The decay resistivity $\rho_{\text{rot}} = 0.03\rho_{\text{wood}}$ is used in the example. The homogenized model is valid if the potential is constant over the trunk cross section.

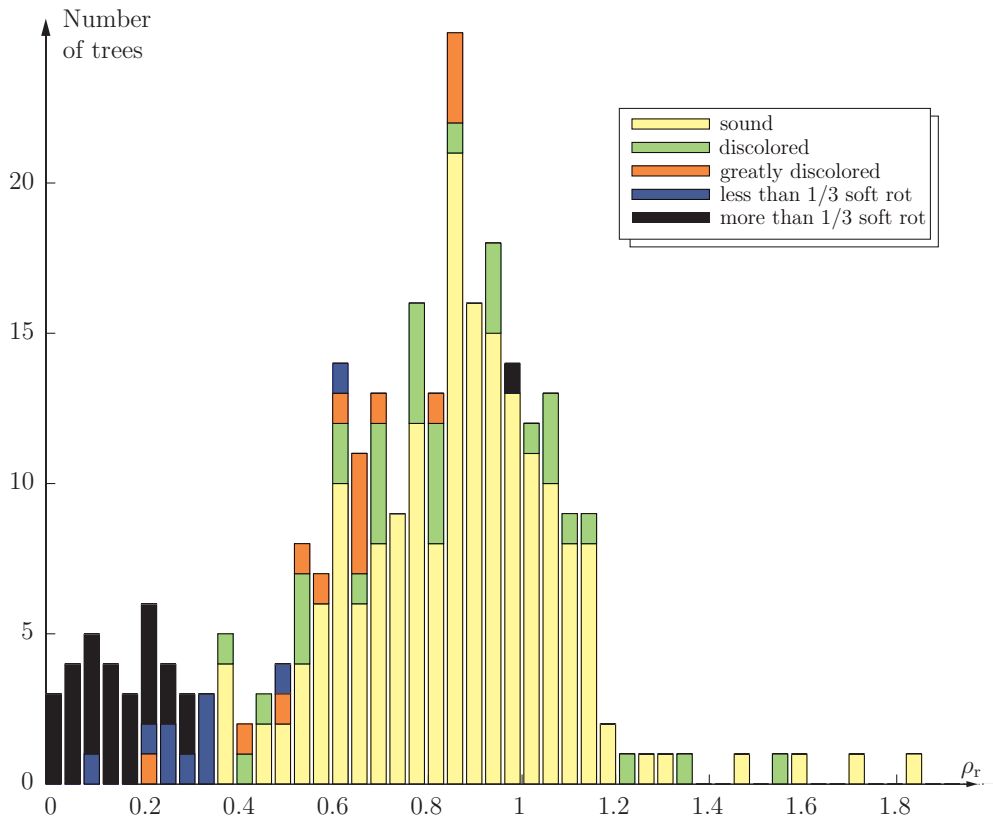


Figure 7: Histogram of 267 spruces from 11 RISE measurement campaigns during 1999–2001. The trees are classified as either sound, discolored, greatly discolored, less than 1/3 soft rot, or more than 1/3 soft rot.

The FEM simulations indicate that the potential variation is small over cross sections away from the feed points. Hence, it is reasonable to use the homogenized model away from the feed points. In the region where the homogenized resistivity model is valid, the voltage variation, *i.e.*, the electric field, is proportional to the effective resistivity. This is illustrated in Figure 8b where the effective resistivity is compared with the quotient between the electric field $E_z = -\partial V/\partial z$ and the induced current I , *i.e.*, the resistivity is scaled such that $\rho = 1$ for a sound tree. The graphs agree fairly well in the region between the connection points. Outside and close to the connection points the homogenized model is no longer valid and hence the graphs differ.

Because of the drastic potential variation close to the connection points it is difficult to construct a reliable apparatus that measures the voltage close to the connection points. This restricts the preferred size of the apparatus. In Figure 9, the relative resistivity is compared to the effective resistivity at the height $z_v = 3r_t$. The current input and output are at $z_{i1}/r_t = 7, 6, 5, 4$ and $z_{i2} = 2r_t$, respectively. The values are scaled such that $\rho = 1$ for a sound tree. Ideally the measured resistivity should be equal to the homogenized resistivity. However, due to the increased resistivity close to the feed points the measured resistivity is larger than

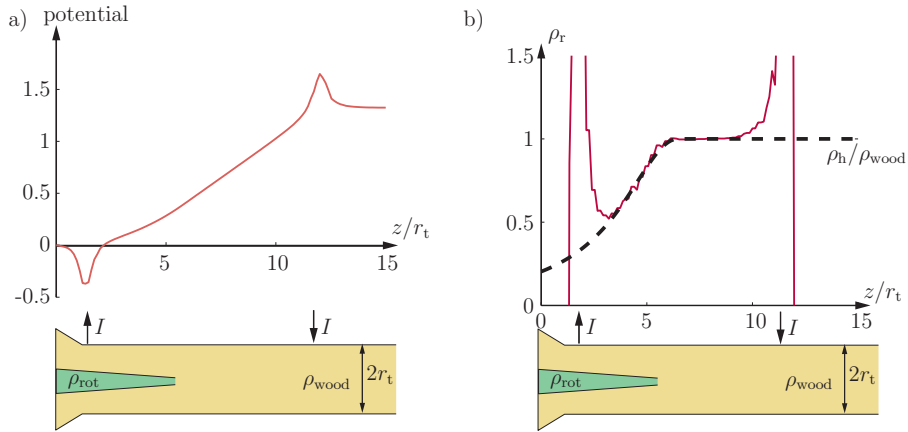


Figure 8: a) Potential distribution along the trunk for a tree with $\rho_{rot} = 0.03\rho_{wood}$. The current is injected and exits at the heights $z_{i1} = 12r_s$ and $z_{i2} = 1.3r_s$, respectively. b) The homogenized resistivity ρ_h/ρ_{wood} compared with the relative resistivity.

the homogenized resistivity. The error increases as the injection point approaches the voltage measurement points. However, even if the difference between the resistivity in a sound tree and an affected tree is clearly observable, the drastic variation close to the connection points makes the voltage measurement sensitive to the location of the measurement probe, *i.e.*, small errors in the probe positioning can produce large errors in the voltage measurement.

5 Discussion

The individual resistivity depends on time of year, type of tree, temperature, and humidity. Therefore it is a risk to sample only one tree and from this predict the amount of decay. The preferred method is rather to measure a group of trees and compare the results. The pattern is then clear: Trees having decay show a lower resistivity than sound trees. The comparison of a sound tree in the summer with a tree with decay at a low temperature in the winter having the same resistivity shows that it would be hard to set an absolute limit for a good/bad decision. Here it is believed that the user has the know-how and makes the final decision based on these facts, the meter reading, and the ocular inspection of the tree. Thus an analog scale is the best way to present the measurement.

There are two major drawbacks with this method. The first drawback is that the exact location of the rot is unknown at a cross section basis, only the amount of decay may be estimated. This is almost always sufficient information. Secondly, even though the example in Figure 3 indicate that the method can be used with frozen wood, this is in general not the case. Since the current transport is due to moving ions the resistivity of frozen wood is several times higher than for normal wood. How this deteriorates the RISE method is a subject of future research. It is also observed that drought can cause problems for the method, *e.g.*, the missed tree

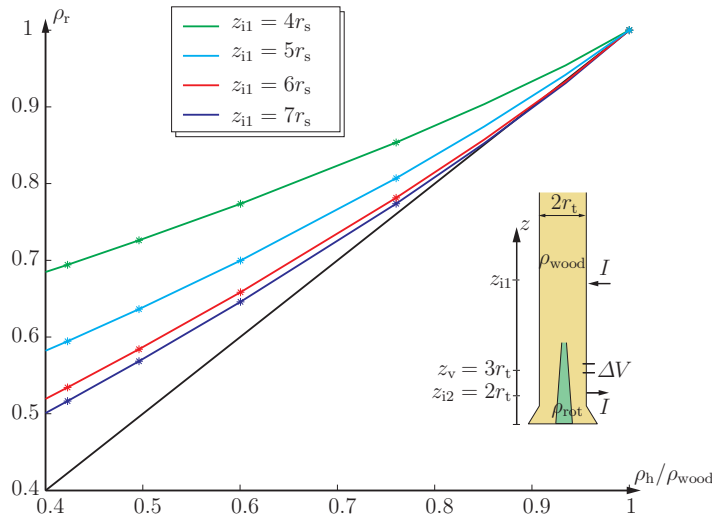


Figure 9: Simulated resistivity compared to the homogenized resistivity for different injection points and decay resistivities. The current is injected at $z_{i1}/r_t = 4, 5, 6, 7$, exit at $z_{i2} = 2r_t$, and the soft rot resistivity decreases from ρ_{wood} to $\rho_{\text{wood}}/50$. The resistivity is determined at the height $z_{v1} = z_{v2} = 3r_t$.

in Figure 7. Drought increases the total resistivity, and probably also reduces the contrast between the resistivity in sound and decay trees. Moreover, it is assumed that it is difficult to detect decay that has caused holes in the trunk, *e.g.*, big cracks and decomposition of the wood. The holes do not conduct electricity and hence the effective resistivity of the trunk increases. The impact of these problems is under investigation.

We find a great need for this simple but effective method. Non-scientific tests, see Section B, have shown that skilled professionals have an accuracy of at most 30%, which is greatly enhanced by our method, with an accuracy of near 100%. The method is also fast. A typical measurement includes to input, the diameter of the tree, attach the free feeding needle at a high place of the trunk and to apply the hand-held unit to the trunk and to read the voltage. This operation should for a trained person take 15 s at the most. The data is stored in the unit and when the entire area is covered data is transferred to, *e.g.*, a laptop.

The desired configuration is one that can be covered with a reasonable sized hand-held unit. This limits the distance to approximately 30 cm (12") which is not feasible according to our measurements. Electrodes in the current path should be at least 40 cm (16") away from the voltage measurement points. The described method is primarily designed for manual use, but it also has a great potential to be used at the harvester-grip. The harvester data processor may evaluate the amount of decay and cut the tree for maximum yield. The possibility to detect rot in dead objects like power-line poles and red core in high-grade wood is also investigated.

Number	District	Date	Trees	Decay
1	Södra Granet	1999-03-20,25,27	31	3
2	Nya Persborg	1999-04-04	15	5
3	Södra Granet	1999-08-30	26	5
4	Norra Granet	2000-09-26	12	0
5	Ekebo Skogsnäbben	2001-02-13,15	40	4
6	Klosterheden	2001-07-22,23	67	9
7	Klosterheden	2001-07-24	20	6
8	Brunsberg, Aplungstorpsäter	2001-08-21	21	0
9	Brunsberg, Åstenäs	2001-09-05	21	5
10	Sävar, Östervik	2001-09-10	22	0
11	Sävar, Nyverket	2001-09-11	22	0

Table 1: RISE measurements in 1999–2001. The locations are shown in Figure 10.

6 Acknowledgments

In the final part of the project we were helped by Forskingscentret for Skov & Landskab, Denmark and by Skogforsk, Sweden, to verify the results. Their support is gratefully acknowledged. We also thank Teknikbrostiftelsen for their support during the initial stage of the project.

Appendix A RISE measurements 1999–2002

The first RISE measurements were performed 1996 at Romeleåsen, Scania, Sweden. Since then several measurement campaigns have been performed in Sweden and in Denmark. In Table 1, the larger (more than 10 trees) RISE measurements between 1999 and 2001 are shown.

Appendix B Comparison between the RISE method and visual inspection

The RISE method to detect decay in spruce has been compared with visual inspection of three professionals. The result is depicted in Figure 11. Each professional filled out a form where he/she graded the probability of each tree to be in decay. Examples of external indication of decay include appearance of fungal fruit bodies, visible decayed wood on old wounds, deteriorated crown, and cracking of soil around an unstable shifting root plate [5]. In Figure 11 the values 0 and 1 correspond to definite decay and sound, respectively. It is observed that the RISE method was very accurate in detecting decay. The method only missed to classify tree number 4 as discolored. The professionals on the other hand were not very accurate. It is difficult to draw any conclusion from this small test except that it is very difficult



Figure 10: Map of Scandinavia showing the location of the RISE measurements in Table 1.

to detect decay only by visual inspection and that the RISE method seems to work well. However, it is believed that the professionals together with the RISE method can be very successful in detecting decay in living trees.

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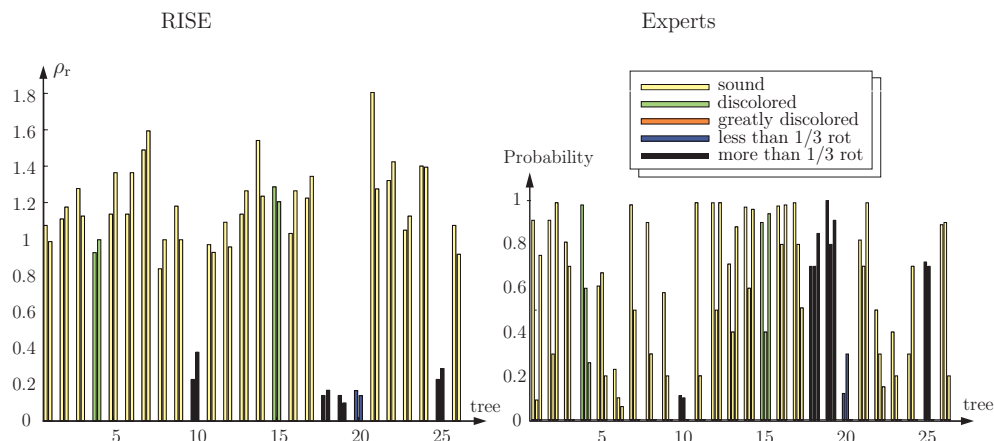


Figure 11: Comparison between the RISE method and visual inspection by three professionals to detect decay in living spruce.

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