Tree Physiology 24, 853–858
© *2004 Heron Publishing—Victoria, Canada*

Nondestructive detection of decay in living trees

BERTIL LARSSON,[1] BENGT BENGTSSON[1] and MATS GUSTAFSSON[1,2]

[1] *Department of Electroscience, Lund Institute of Technology, Box 118, 211 00 Lund, Sweden*

[2] *Corresponding author (Mats.Gustafsson@es.lth.se)*

Received March 3, 2003; accepted December 3, 2003; published online May 3, 2004

Summary We used a four-point resistivity method to detect wood decay in living trees. A low-frequency alternating current was applied to the stem and the induced voltage measured between two points along the stem. The effective resistivity of the stem was estimated based on stem cross-sectional area. A comparison within a group of trees showed that trees with butt rot had an effective resistivity that was at least a factor of two lower than that of healthy trees. In tests on several groups of Norway spruce (*Picea abies* (L.) Karst.) comprising more than 300 trees in total, the method detected butt rot with high accuracy. We validated the method both by measurements and by finite element modeling and simulations.

Keywords: butt rot, four-point resistivity method, fungal infections, Norway spruce, Picea abies, RISE, stem resistivity.

Introduction

A large percentage of living trees have some kind of decay that reduces their economic value. Trees with decay are usually either left to decompose or are used as fuel wood. In 2001, timber losses in Sweden caused by decay equaled 15% of the annual harvest. An accurate method of detecting decay in living trees would be useful both during the harvesting process and when forested land is assessed for sale or for designation as a conservation area. Such a method is described here.

Infection of trees by wood decay fungi occurs mostly in roots, where damage to the bark allows fungal invasion. Fungal infections can also spread by way of the grafted roots of neighboring trees. As the fungus invades the stem, it causes movement of water to the area of mycelial growth, thereby mobilizing metal ions released by damaged tree cells. This causes a decrease in the resistivity of the affected wood compared with healthy wood (Shortle and Smith 1987).

The resistivity of living tree stems can be investigated with a shigometer, a device that delivers a pulsed electric current to the wood tissue and measures tissue resistance to the current (Tattar and Shigo 1972, Shortle and Smith 1987, Smith and Shortle 1988, Ostrofsky and Shortle 1989, Butin 1995). The shigometer electrodes, which are inserted into a narrow hole drilled toward the center of the stem, measure variation in resistivity along the length of the hole. Although the shigometer can detect decay at an early stage and the use of a narrow hole reduces the extent of injury, a noninvasive method is preferable. Impedance tomography is a nondestructive method that gives an image of the resistivity of the stem (Weihs et al. 1999). However, the large number of sensors required and time-consuming nature of the measurements make this method unattractive for routine monitoring for decay. Various other nondestructive methods are based on X-ray tomography (Habermehl 1982), microwave scanning (Martin et al. 1987), magnetic resonance imaging (Müller et al. 2001) and acoustical methods (Waid and Woodman 1957, Wilcox 1988, Bethge et al. 1996, Axmon 2000). Nondestructive methods of testing wood have been reviewed by Bucur (2003).

We tested the effectiveness of the relative impedance in situ examination (RISE) method (Bengtsson 1997) for detecting decay in living trees. This simple four-point method is based on estimation of effective resistivity, the difference in induced voltage between two points along a stem. Decay can be detected by comparing the effective resistivity of a single tree to that of other trees measured under similar conditions, i.e., temperature, humidity, site conditions and time of year. To validate the four-point method, eleven measurement campaigns were carried out and more than 300 Norway spruce trees were examined.

Materials and methods

Four-point resistivity (RISE) method

We modified the four-point resistivity method described by Popović and Popović (2000). Four-point measurements are made by passing a current through an object with one pair of electrodes, while measuring the voltage difference with another pair of electrodes (Figure 1). A healthy tree gives a higher voltage difference than a decaying tree because decay reduces tissue resistivity. The resistance normalized for stem cross-sectional area provides an absolute value of resistivity that is related to the amount of decay.

We define effective resistivity (ρ) as the resistance of a stem section, when a constant current is passed vertically through the stem and the voltage is measured at two points on the stem surface:

$$\rho = \frac{\Delta VA}{Il} \tag{1}$$

where ΔV is voltage difference, I is current, l is distance between the measuring points, and A is the stem cross-sectional area.

The advantage of this method compared with the two-point method is that neither the resistance of the current cables nor the contact resistance at the feeding points causes any measurement errors.

A reference electrode is placed between the voltage measuring electrodes to obtain a noise-free voltage reading. The voltage contact pins are thin needles, but could be any contact surface, because the current flowing in the voltage sensors is low. We used a low-frequency alternating (300 Hz) current that was signal-processed to eliminate disturbance caused by galvanic elements that appear between the metal pins and the electrolytic sap.

The effective resistivity of wood depends on water content and temperature (Panshin and de Zeeuw 1970, Torgovnikov 1993), making it difficult to use the resistivity of an individual tree for the detection of decay. Instead, resistivity of an individual tree is compared with that of other trees measured under similar conditions. Relative resistivity (ρ_r) is defined as:

$$\rho_r = \frac{\rho}{\rho_{sound}} \quad (2)$$

where ρ_{sound} is the mean resistivity of apparently health trees. Thus, relative resistivity normalized to a value around one for healthy trees.

Results

We undertook 11 measurement campaigns to evaluate the reliability of the RISE method and found that resistivity depends on time of year, type of tree, temperature and humidity. Therefore, one cannot sample a single tree and from this predict the amount of decay. Instead, a large group of trees must be measured and the resistivities of the trees within the group compared. The resistivity values of three Norway spruce trees are shown in Figure 2a. Measurements were performed between September 2001 and September 2002. Based on visual assessments of core drill samples, trees were classified into three groups: decayed, discolored and healthy. The resistivity of the tree with decay from January 1, 2002 was higher than the resistivity of the healthy tree from the other dates. The high resistivity values on January 1, 2002 are probably a result of the low temperature (−6 °C) before and during the measurement. Dependence on time of year and temperature was reduced by comparing relative resistivity values (Figure 2b). In this case, the tree with decay and the discolored tree had relative resistivity values of about 0.15 and 0.6, respectively.

Figure 3 shows the relative resistivity for 10 Norway spruce trees at Romeleåsen, Scania, Sweden. Measurements were made on six occasions from May to September 2001. Although relative resistivity varied among trees, Trees 7 and 9 had substantially lower relative resistivities than the other trees. After felling on October 23, 2001, photographs of stem sections were taken (Figure 4). Colored zones of decayed tissue were clearly visible for Trees 7 and 9.

Two measurement configurations were compared in Figure 3. For the results shown in Figure 3a, the standard procedure was followed; current was applied at a height of 2.3–2.6 m and exited through the ground. Voltage was measured between points 10 cm apart at heights of 10 and 50 cm above ground. For the results shown in Figure 3b, the height of the measurement equipment was lowered to 80 cm and the voltage was measured between points 10 cm apart and midway between electrodes by which the current was applied. Results were similar for the two configurations.

The RISE method can be used to determine the vertical spread of decay in the stem. Results shown in Figure 5 were

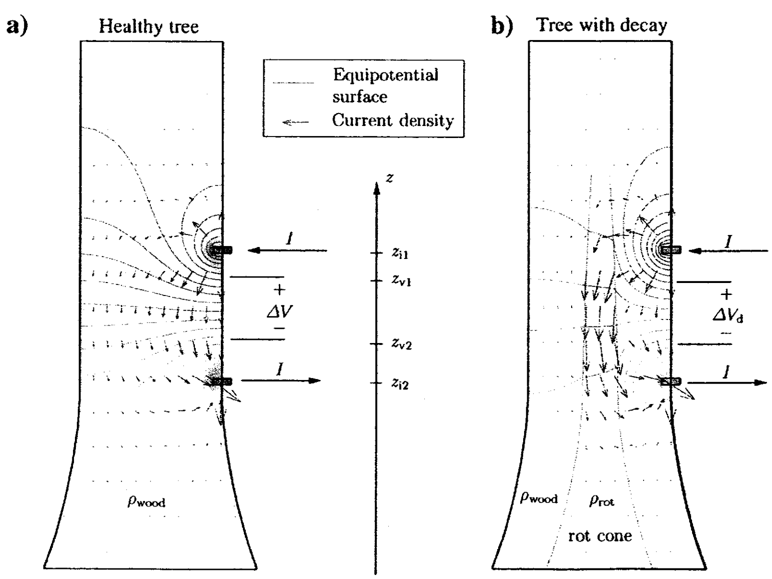

Figure 1. Diagram illustrating the four-point resistivity method. Current was applied at height z_{i1} and exited at z_{i2}. Effective resistivity (ρ) was determined as $\rho = \Delta VA/Il$, where ΔV is difference in voltage; A is the cross-sectional area, I is the current, and l is the distance between z_{v2} and z_{v1}. (a) Healthy tree showing that the current is distributed over the whole stem cross section. (b) Tree with butt rot showing that resistivity is relatively low in the cone-shaped decayed region and that the current is concentrated in the region of decay. The measured voltage (ΔV) was lower for the tree with decay than for the healthy tree.

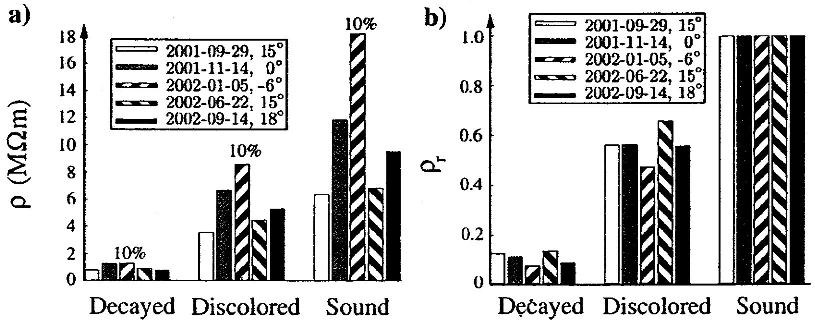

Figure 2. (a) Comparison of the effective resistivity (ρ) and (b) relative resistivity (ρ_r) in three Norway spruce trees at Romeleåsen, Scania, Sweden. Measurements were made on five occasions between September 2001 and September 2002. Temperature at time of measurement was as indicated. Note that the values from January 2002 on are scaled to 10% to fit in the graph.

obtained by applying the current to the stem at a height of 4.4 m and allowing it to exit through the ground. Resistivity was measured at heights of 0.1, 1.0 and 2.0 m. The measurements were repeated for north, west, south and east directions. A comparison of the values with the cross-sectional photographs indicates that the RISE method gave information about the location of the decay in the vertical direction only.

The RISE method allows comparison among similar trees measured under the same conditions at the same time of year. Therefore, to classify the trees as healthy, discolored or decayed, it is necessary to have a sufficiently large group of healthy trees for comparison. In our study, the healthy and decayed trees had a relative resistivity around 1 and 0.5, respectively (Figure 3). However, the mean resistivity depends on the relative proportions of healthy and diseased trees in the group. To reduce the coupling between relative resistivity and the composition of the group, we normalized the resistivity with respect to the mean resistivity of the apparently healthy trees.

Between 1999 and 2002, we examined about 300 Norway spruce trees with the RISE method. Figure 6 shows a histogram of the normalized relative resistivities of 267 trees from 11 measurement campaigns. Tree classification was based on examination of photographs of either stem cross sections or core drill samples. Although several groups of trees were combined in the histogram and the normalization was performed in a simple fashion, a general trend is evident. Low values of 0–0.4 corresponded to trees classified as decaying or greatly discolored, whereas values over 0.8 corresponded to trees classified as healthy or discolored. Trees with ρ_r values between 0.4 and 0.8 were not easily classified as decayed, discolored or healthy. We note that the subjective classification of trees based on the photographs was a major source of error. For example, the diseased tree with a relative resistivity of about 1 was not due to an incorrect classification. Inspection revealed that the tree was mechanically damaged and its high relative resistivity was probably associated with drought stress.

Electrical modeling

To gain further insight into the RISE method, we applied the the Finite Element Method (FEM). For a tree with given geometry, resistivity and measurement setup, the FEM is used to determine the induced voltage from an applied current and hence the resistivity. The healthy tree is modeled as a cylindrical stem with a conical root. Both the stem and the root are assumed to have resistivity ρ_{wood}. The affected part of the tree is modeled as two cones. The inner cone, constituting the decayed region, has resistivity ρ_{rot}, and is surrounded by the humid front layer with resistivity ρ_{front} (see also Butin 1995,

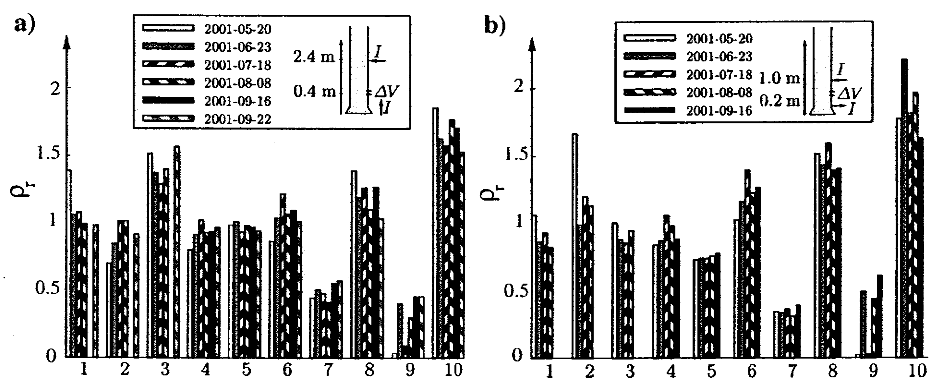

Figure 3. Comparison of the relative resistivity (ρ_r) of 10 Norway spruce trees at Romeleåsen, Scania, Sweden. Measurements were made on six occasions from May to September 2001. Some values are missing because poor weather prevented measurements from being made. Photographs of the corresponding stem cross sections are shown in Figure 4. (a) The standard RISE measurement in which the current was applied at a height between 2.3 and 2.6 m and exited through the earth. (b) RISE measurement with 80 cm between the current application electrodes.

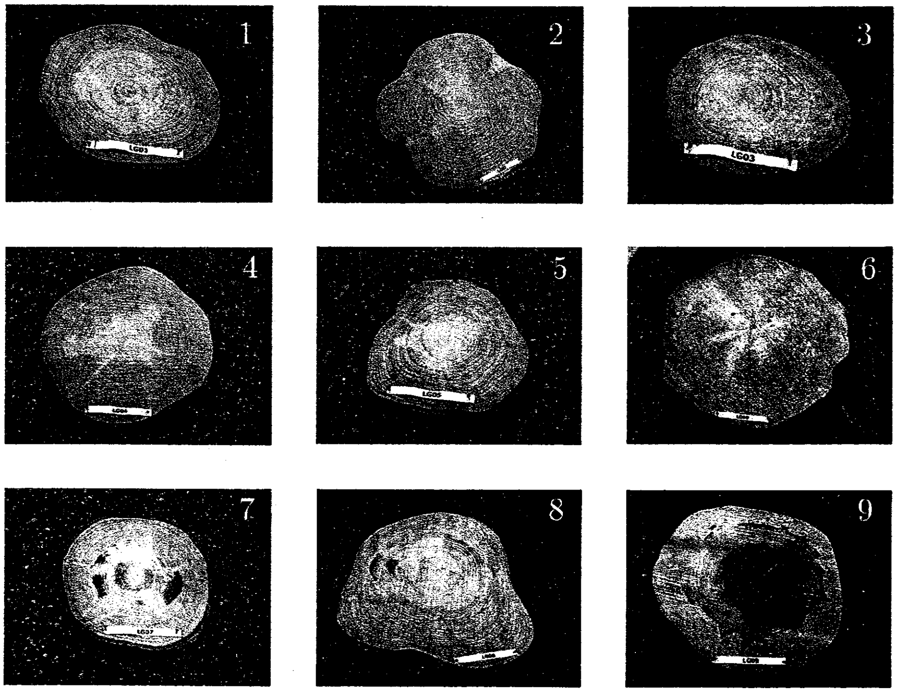

Figure 4. Photographs of stem cross sections of the Norway spruce trees in Figure 3. The trees were felled in October 2001. Photographs 1–6 and 8 are healthy trees. Tree 7 had dark flecks and Tree 9 had a region with fibrous decay. Tree 10 (not shown) was healthy.

Chapter 7). The resistivity in wood is generally anisotropic, i.e., the resistivity depends on direction. To understand how the resistivity depends on the measurement setup, a simplified case with isotropic resistivity and a front layer resistivity $\rho_{front} = \rho_{rot}$ was analyzed. The current was applied to the stem at z_{i1} and exited at z_{i2} (see Figure 1).

A parametric study was performed to determine how the voltage distribution along the stem depends on the shape of the affected part and to analyze the difference between the resistivity in the affected part and the resistivity in the stem. From the FEM simulations, we concluded that the voltage depends weakly on root shape. In the following analysis, we used a root cone with radius, $r_r = 1.2r_s$, and height $z_r = 0.8r_s$, where r_s is the radius of the stem.

We observed that the potential changes rapidly close to the current application points (Figure 7). The potential dropped from its highest value at the application point to its lowest value at the exit point. Away from the connection points, the potential change was less and hence it was possible to relate the potential distribution on the surface of the stem to the effective resistivity inside the stem. The effective stem resistivity ($\rho(z)$) as a function of the height z was obtained as a parallel connection by:

$$\frac{A}{\rho(z)} = \frac{A_{rot}(z)}{\rho_{rot}} + \frac{A - A_{rot}(z)}{\rho_{wood}} \tag{3}$$

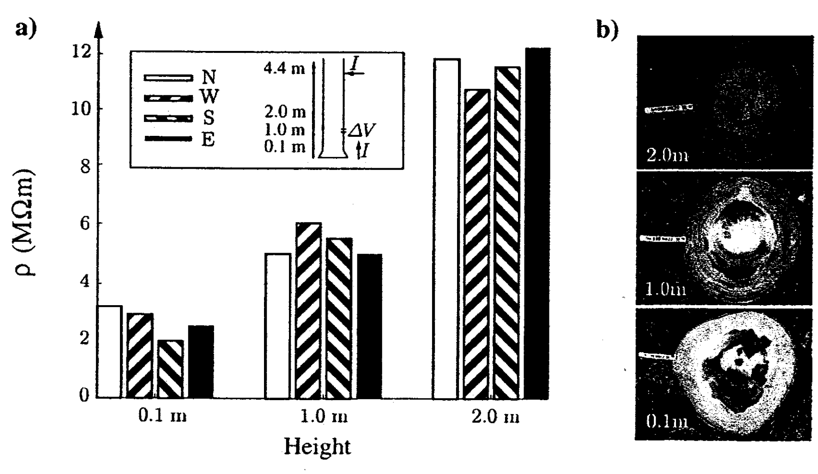

Figure 5. (a) The resistivity of an infected Norway spruce tree at heights of 0.1, 1.0 and 2.0 m. The current was applied at a height of 4.4 m and exited through the earth. (b) Photographs of the corresponding stem cross sections. Markers located on the left of each stem point westward.

decay that has resulted in lacunae in the stem because cavities do not conduct electricity and thus increase stem resistivity. Fifth, decreased resistivity precedes the mechanical degradation of wood (Smith and Shortle 1988). Hence, decreased resistivity may not correspond to loss of wood value.

Drawbacks, notwithstanding, the RISE method can achieve an accuracy close to 100% in identifying trees with decayed stems. Each measurement, which involves determining tree diameter, attaching the free current application electrode to the stem, applying the hand-held measurement unit to the stem and reading the voltage, can be completed in about 15 s by a trained operator.

Acknowledgments

Forskingscentret for Skov & Landskab, Denmark and Skogforsk, Sweden helped verify the results of this experiment. Their support is gratefully acknowledged. We also thank Teknikbrostiftelsen for their support during the initial stage of the project.

References

Axmon, J. 2000. On detection of decay in growing Norway spruce via natural frequencies. Licentiate Thesis, Lund Inst. Technology, Dept. Appl. Electronics, Lund, Sweden, 105 p.

Bengtsson, B. 1997. Anordning och användning vid detektering av röta-angrepp i biologiskt material, företrädesvis träd. Swedish Patent No. 9703540–6.

Bethge, K., C. Mattheck and E. Hunger. 1996. Equipment for detection and evaluation of incipient decay in trees. Arbor. J. 20:13–37.

Bucur, V. 2003. Nondestructive characterization and imaging of wood. Springer-Verlag, New York, 324 p.

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

Habermehl, A. 1982. A new non-destructive method for determining internal wood condition and decay in living trees. I. Principles, method and apparatus. Arbor. J. 6:1–8.

Jartti, J. 1978. On the measurement of internal decay in living trees. Silva Fenn. 12:140–148. In Finnish.

Martin, P., R. Collet, P. Barthelemy and G. Roussy. 1987. Evaluation of wood characteristics—internal scanning of the material by microwaves. Wood Sci. Technol. 21:361–371.

Müller, U., R. Bammer, E. Halmschlager and R. Wimmer. 2001. Detection of fungal wood decay using magnetic resonance imaging. Holz Roh-Werkstoff 59:190–194.

Ostrofsky, W.D. and W.C. Shortle. 1989. Application of the shigometer for assessing tree and forest health and wood product quality. Rev. Trop. Plant Pathol. 6:39–57.

Panshin, A.J. and C. de Zeeuw. 1970. Textbook of wood technology. 3rd Edn. McGraw-Hill, New York, 736 p.

Popović, Z. and B.D. Popović. 2000. Introductory electromagnetics. Prentice-Hall, Englewood Cliffs, New Jersey, 556 p.

Shortle, W.C. and K.T. Smith. 1987. Electrical properties and rate of decay in spruce and fir wood. Phytopathology 77:811–814.

Smith, K.T. and W.C. Shortle. 1988. Electrical resistance and wood decay by white rot fungi. Mycologia 80:124–126.

Tattar, T.A. and A.L. Shigo. 1972. Relationship between the degree of resistance to a pulsed electric current and wood in progressive stages of discoloration and decay in trees. Phytopathology 62:792.

Torgovnikov, G.I. 1993. Dielectric properties of wood and wood-based materials. Springer-Verlag, Berlin, 196 p.

Waid, J.S. and M.J. Woodman. 1957. A nondestructive method of detecting diseases in wood. Nature 180:47.

Weihs, U., V. Dubbel and F. Krummheuer. 1999. Die Elektrische Wiederstandstomographie—Ein vielversprechendes Verfahren zur Farbkerndiagnose am stehenden Rotbuchenstamm. Forst. Holtz 6:166–170.

Wilcox, W.W. 1988. Detection of early stages of wood decay with ultrasonic pulse velocity. For. Prod. J. 5:68–73.