Electrical measurement of the absorption surfaces of tree roots by the earth impedance method: 1. Theory

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Summary   Analysis of plant root systems is difficult under field conditions, especially root systems of adult trees, which are large and complex and include fine absorbing roots as well as conducting coarse roots. Although coarse roots can be visualized by several methods, there are technical difficulties with root quantification. The method presented here focuses on the quantification of absorbing root surfaces through an electrical (the modified earth impedance) method. It is based on the experimentally verified fact that an applied electric current flows from the roots to the soil (or vice versa) through the same interfacial areas and predominantly in the same way as water (water solution of minerals or nutrients) flows from the soil to the tree. Based on the different conductivities of tree tissues and soil, the interfacial area, which represents the absorbing root surfaces (or root absorption zones), can be calculated. Only the theoretical description of the method is presented in this paper: the experimental verification of the method under field conditions is presented in the accompanying paper.

Keywords: absorbing root surfaces, absorption zones, electrical resistivity and conductivity, four-point method.

Introduction

Measurement of root systems in woody species under field conditions is difficult, especially root systems of adult trees, which are large and complex and include fine absorbing roots as well as conducting coarse roots. Root absorbing surfaces or absorption zones (AZ) represent compartments through which plants absorb soil water (i.e., a dilute solution of mineral elements). The size and permeability of AZ are crucial parameters for plant survival. We tried to solve the problems associated with measuring AZ of large root systems by a non-traditional physical approach based on the work of Staněk (1997), who applied the findings of earlier studies (e.g., Flerov et al. 1981, Sorocanu 1983, Repo 1988). This paper describes the theory underlying the earth impedance method. If a plant root system is submerged in aqueous solution and connected to a simple electric circuit, the electric current from the external source (represented by ion flow) enters the root through the electrically conducting (ion absorbing) root surfaces. Because other root surfaces do not conduct electric current, we can esti-

mate the soil–root interface based on the differences in conductivity of the various root tissues and soil and hence, the conducting or absorbing root surface area. Verification of results obtained by this method is discussed in the accompanying paper (Čermák et al. 2006).

Measurement of absorbing root surfaces by the earth impedance method

Experimentally verified assumptions

A. Integral electrical conductivity (specific electrical conductance) of plants (and similarly of their components, such as cell walls) depends on the presence of ions in water, electron conductivity being negligible. Plants belong to the heterogeneous electric conductors of Class II, i.e., heterogeneous aqueous electrolytes, but represent a unique group within the class. When a plant becomes a component of an electric circuit, the principle of electric current continuity applies.

B. A living, healthy and uninjured plant cell is a relatively poor conductor of electric current because the cell walls have an electrical resistivity (specific electrical resistance) equivalent to the resistivity of technical insulators of Class II ($\approx 10^4$–10^{10} Ωm). A set of cells, i.e., a piece of woody tissue, represents a system of resistance barriers in the form of cell walls, as do the water-filled intercellular spaces paralleling the ion pathway. Electric conductivity of such systems is multidirectional. However, when the plant cells are of the same type, such as parenchyme or sclerenchyme cells, anisotropy prevails. Only severe cell injury or death causes a substantial decrease in tissue resistivity (up to several orders) and usually also to the decay of anisotropy.

C. The introduction of a constant external electric current to a plant is impossible without injury to some cells.

D. Walls of uninjured epidermal cells covered by a cuticle are especially good barriers to the flow of electric current, e.g., leaf and bark surfaces, as well as most root surfaces.

E. Exceptions to the general rule of low electrical conductivity in plant cells are conducting elements (vessels and tracheids) and phloem sieve tubes. Water-conducting elements (i.e., pipes with almost open ends) are not only good conductors of water or water solutes, but also allow almost unrestricted ion movement. Electrical conductivity of stems, bran-

ches, shoots and roots is mostly determined by the conductivity of the apoplast (i.e., water-filled vessels and tracheids). The remaining, less conductive living part of cells (symplast) is attached to the conductive elements in parallel, which increases total conductivity. Electrical conductivity is therefore directional and water-conducting tissues are anisotropic. An electric circuit simulating the conductive situation in plant tissues comprises a parallel combination of resistances and capacitances (several such schemes have been proposed over the last 20 years).

F. Electric current presumably flows from the soil to roots through root absorption surfaces. Electric current can also flow through impermeable walls of other cells, but with a negligible density (see scheme in Figure 2). Direct contact between roots and wet or dry soil or even water has little impact on current flow. We considered direct current and alternating current with low frequency.

G. Electrical conductivity of living woody tissues has a resistive–capacitive character (see item E). Cell walls, including walls of vessels, represent the capacitive components. Inner parts of cells (symplast) and water-filled intercellular spaces represent resistive components. Cell walls are involved to only a small extent, which is why the resistive and capacitive components of electrical conductivity are dispersed.

H. For alternating current, resistivity is a complex number and is therefore dependent on frequency. A phase shift occurs when the alternating current flows from the external source between two points along the surface of woody tissues. This shift is not constant. It is dependent on frequency and also on some specific plant parameters, e.g., phenological phases. Resistivity for alternating current is always smaller than resistivity for direct current.

I. Resistivity of living plant tissues for both direct and alternating currents decreases with increasing temperature, usually in a slightly nonlinear manner because plant tissue is a heterogeneous electrolyte.

J. The temperature dependence of resistivity changes with time. The main changes correspond to phenological phases. Both simple and complex resistivity of a specific plant organ remain unchanged at the same temperature and phenological phase.

K. Resistivity of living plant tissue is voltage dependent. This dependency must be considered when selecting the most suitable measuring voltage.

L. The input of electrical current into plant tissues from an external source, e.g., through the insertion of metal electrodes, can result in electric breakdown (loss of insulation properties of material due to excessive voltage) as a result of permanent injury of the cells surrounding the electrode. Electric breakdown usually becomes apparent as a result of local overheating (e.g., a rise in temperature above 40 °C close to the electrode tips).

M. Resistivity is not distributed homogeneously along geometrical cross sections of stems and branches or root because the electrical conductivities of vessels, tracheids and other cells differ. Electrical conductivity is substantially lower in dead heartwood than in living woody tissues. The most pronounced and abrupt change in electrical conductivity occurs at the edge of the sapwood and heartwood.

N. Permeable cell walls of the absorption zones and the water-conductive elements (vessels and tracheids) represent a continuum.

O. The resistivity and its reciprocal value, conductivity, are not material constants in plants (or in other water electrolytes).

Illustration of the principle underlying the earth impedance method in a hypothetical plant

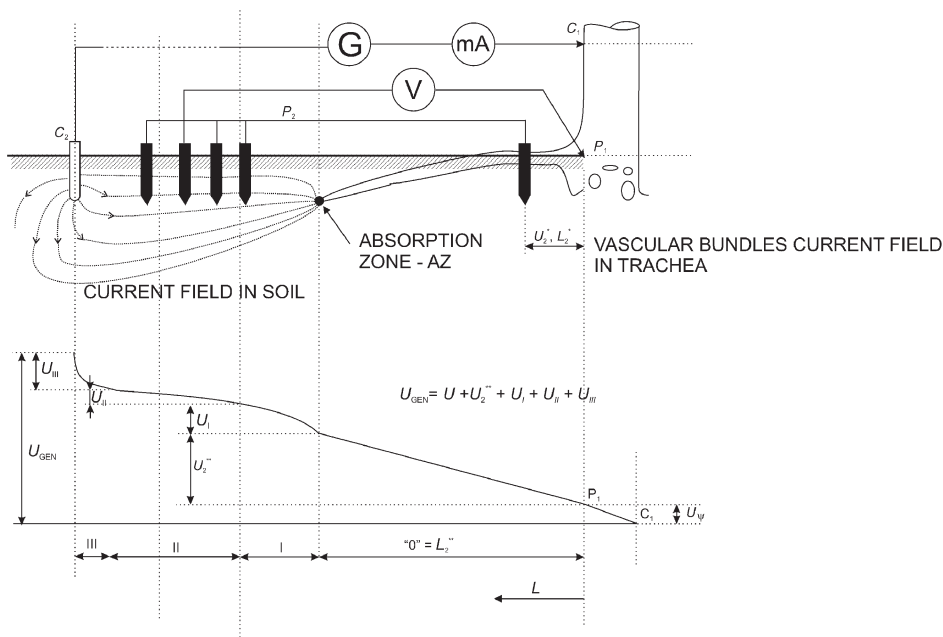To illustrate the principle of the earth impedance method, we

Figure 1. Current field in soil for hypothetical wood comprising a single root having a single absorption zone. Abbreviations: G = low frequency power supply; mA = milliammeter; V = voltmeter; C_1 = current electrode in the stem; C_2 = current electrode in the soil; P_1 and P_2 = potential electrodes; U_Ψ = potential drop from electrode P_1 to electrode C_1; U_2^* = potential difference between electrode P_1 and electrode P_2 in distance L_2^* from the stem; U_I, U_{II} and U_{III} = potential differences on sections I, II and III, respectively; U_{GEN} = voltage on generator; U_2^{**} = potential drop between P_1 and end of root; L_2^{**} = length of root; and "0" = root tissue section.

$$U_{GEN} = U + U_2^{''} + U_I + U_{II} + U_{III}$$

consider a hypothetical plant with a single root with a single vessel and a single AZ on its surface (Figure 1). The electrical circuit comprises the root, part of the plant stem, a source of electric current (electrodes C_1 and C_2 inserted into the plant and soil) and an ammeter. Voltage is measured by a voltmeter connected to potential electrodes P_1 and P_2. The current can be direct or alternating with a low frequency (hundreds of Hz) and a sinusoidal waveform.

The proposed method for determining the distances between soil electrodes and the experimental tree, and the distances between the electrodes themselves depends on the potential characteristic, i.e., the distribution of potentials (voltage) between the current electrode in the stem (C_1) and the current electrode in the soil (C_2) in a selected radial direction. The potential characteristic has several distinctive sections. The first section is between C_1 and P_1 (Figure 1) and is marked by the length ψ and voltage drop U_ψ. The following Section "0" is within the root tissues and represents a part of the distance between P_1 and P_2. The most important section from the viewpoint of the measurements is the nonlinear Section I in the soil, which is close to AZ on roots, and its transition to the linear Section II. Section III is relatively steep and nonlinear.

Section III represents the gradually diminishing spatial extent of the electric field in soil with decreasing distance to electrode C_2. The potential characteristic shows that the distribution of potentials is dependent on distance from the stem in a single radial direction (Figure 1). It is measured on the soil surface by moving electrode P_2 in steps of known length, reading voltage simultaneously. A plot of potentials against distance from the stem illustrates the density of equipotential areas, which are present in any point of soil half-space and are perpendicular to the current filaments. Current entering the tree through electrode C_1 leaves the tree and enters the soil in the region of the absorbing root surfaces, which is why the highest density of current filaments is at AZ.

The potential characteristic (Figure 1) determines the optimum position of C_2 in relation to the measured tree. It corresponds to the distance that allows clear recognition of Section II. The potential characteristic also determines the I–II interface on the soil surface, which helps determine the place where the potential electrode P_2 should be inserted when measuring absorbing root surfaces. In the case of a hypothetical plant with a single absorption zone, P_2 is inserted at distance L from P_1 (or from the tree).

The presumed relationships and contacts at the surface of the AZ (soil–root contact) are shown in Figure 2. To quantify them, we start with the general equation of current continuity according to Figure 3:

$$\oiint_S \vec{j}\,d\vec{S} = \oiint_{S_1} \vec{j}\,d\vec{S} + \oiint_{S_2} \vec{j}\,d\vec{S} = -I + I = 0 \tag{1}$$

where S is the total conductor surface, $d\vec{S}$ is a vector element of the surface, S_1 and S_2 are conducting root surfaces through which the current enters (or exits) the conductor (= root), $\vec{j}$ is a vector of current density, and $+I$ and $-I$ are currents entering or
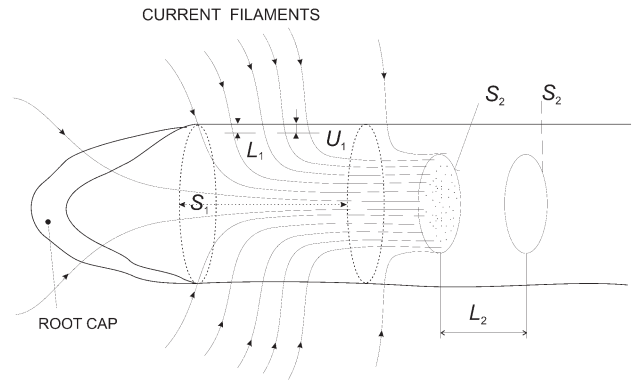

Figure 2. Current field in the neighbourhood of the root ending with absorption zone S_1. Abbreviations: S_1 = conducting root surfaces through which the current enters; S_2 = conducting root cross sections; L_1 = thickness of absorption zone S_1; L_2 = distance between cross sections in root; U_1 = potential drop on distance L_1; and U_2 = potential drop on distance L_2.

exiting the conductor.

For a single root and its interface with the soil, the continuity equation has the form:

$$I = \frac{U_1}{R_1} = \frac{U_2}{R_2} = \frac{U_1 S_1}{\rho L_1} = \frac{U_2 S_2}{\rho L_2} \tag{2}$$

where ρ is the electrical resistivity of the root interface, which we assumed is equal to the resistivity of the soil close to the root interface.

The magnitude of the areas (surfaces) S_1 and S_2 is given by:

$$S_1 = \frac{I}{U_1}\rho L_1 \tag{3}$$

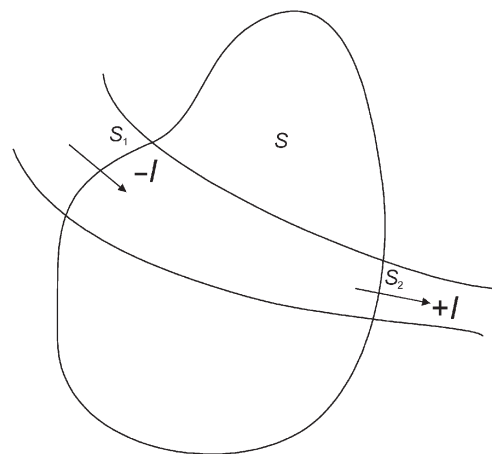$$S_2 = \frac{I}{U_2}\rho L_2 \tag{4}$$

Figure 3. Illustration of the continuity equation. Abbreviations: S_1 and S_2 = conducting root surfaces through which the current enters; $-I$ and $+I$ = currents entering or exiting the conductor; and S = the total conductor surface.

We are most interested in area S_1 (or magnitude of conducting root interface surface). Unfortunately, we cannot determine U_1 or L_1 from Equation 3, because we cannot define them clearly. However, on the basis of continuity between the electrically conducting root surface and the water-conducting clusters of vessels, the condition that $S_1 = S_2$ and is always smaller than the geometric cross sections of roots is satisfied, so:

$$S_1 = S_2 = \frac{I}{U_2}\rho L_2 \qquad (5)$$

In principle, U_2 and L_2 can be determined in two ways, as shown in Figure 1 (where the ratio of $L_2/U_2 = L*_2/U*_2$ remains constant). We can measure this ratio on the root just below the root collar. Alternatively, we can determine the ratio above in the following way: the potential electrode P_2 is inserted in the soil at the point of contact of Sections I and II or somewhere in Section II of the potential characteristic (Figure 1). Electrode P_1 is inserted in the sapwood at the soil–stem interface or the root–stem interface. Both electrodes (P_1 and P_2) then occur at a distance L_2, and Equation 5 takes the form:

$$S_1 = S_1 = \frac{I}{U_2^*}\rho L_2^* = \frac{I}{U_2^{**}}\rho L_2^{**} \qquad (6)$$

Before considering real trees with many roots and absorbing root surfaces, we have to consider the following differences between real plants and the hypothetical plant. (1) The electrical resistivity of sapwood in stems and in the main coarse roots is not necessarily the same as the resistivity of absorbing root surfaces. (2) The root radius is not equal to the electrical root radius (L_2^*). The electrical root radius is usually substantially smaller than the geometrical radius and it generally characterizes the location of the largest coarse roots in the soil. (3) The course of potential characteristic and distances to Sections I and II from the stem differ in each radial direction. Notwithstanding these large physical differences between hypothetical and real plants, the mathematical approach for estimating absorbing root surfaces is similar in both cases.

Application of the earth impedance method to measurement of absorption zones of a root segment

We now replace the hypothetical plant possessing a single root with a real plant and any of its major (single) roots and all roots connected with it. Hereafter, we will call such a root a "root segment." We will use the term "main root" to refer to the cluster of all roots occurring in a radial direction with respect to the soil current electrode.

A potential characteristic of a root segment is shown in Figure 4. We can distinguish three (or four) regions. Their locations relative to the roots and tree stem are different from that in a hypothetical plant because individual absorbing root surfaces occur at different distances (L_x) from the tree base. The greatest distances correspond to the longest roots and vice versa. This is why we use mean distance (L_{mean}), which corre-
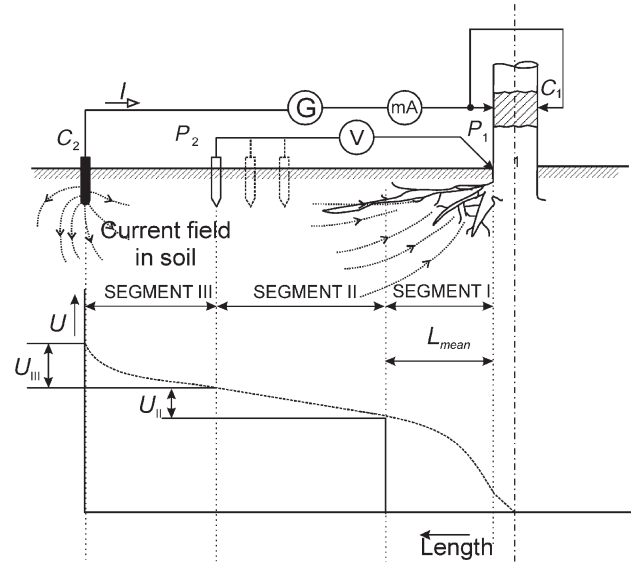

Figure 4. Current field in soil for real wood. Abbreviations: I = current; C_1 = current electrode in the stem; C_2 = current electrode in the soil; P_1 and P_2 = potential electrodes; G = low frequency power supply; mA = milliammeter; V = voltmeter; U = voltage axes; U_{II} and U_{III} = potential differences on segments II and III, respectively; and L_{mean} = mean distance.

sponds to the distance of the interface between Sections I and II of the potential characteristic from the stem base, or the potential electrode P_1 inserted there. The value of L_{mean} is therefore always less than the longest segment roots.

During measurement, electric current flowing from the tree stem to the surrounding soil through a root segment decreases with increasing distance between electrodes L and the place taken as L_{mean}. During measurements, the fraction of current in the roots cannot be distinguished from the fraction of current leaving and entering the fine absorbing roots in the root segment.

We substituted ρ for soil resistivity in Equations 5 and 6 for the hypothetical plant because critical parts of the potential characteristic were in the soil. When considering a real root segment, however, we have to substitute the resistivity of woody tissues (ρ_{wood}) for ρ because the critical part of the potential characteristic for estimating the absorbing root surface is along the root segment.

The ρ_{wood} of fine roots is assumed to be equal to that in stems and main root sapwood, although deviations from this assumption occur in reality. Resistivity of the thinnest fine roots is 8 to 10 times less than the resistivity measured in stems or main coarse roots. Section "0" of the potential characteristic (Figure 1) corresponds to this situation. Resistance U/I increases with root length, but tissue resistivity decreases with root length concurrently.

The value of ρ_{wood} for calculating absorbing root surfaces can be obtained by measuring ρ_{wood} in any part of stems or coarse roots associated with the given root segment because the major part of the root segment (L_{mean}) through which current flows comprises tissues in which the resistivity is equal to

the resistivity of the stem (or coarse root) sapwood and the ends of roots have low electric resistance. The equation for calculating the total absorbing root surface in the measured root segment is:

$$S_{AZ} = \frac{\rho_{wood} L_{mean} I}{U} = \frac{\rho_{wood} L_{mean}}{R} \qquad (7)$$

The current flowing through the root segment to the surrounding soil is included in Equation 7 in addition to the above-mentioned variables and the slope of voltage measured between the potential electrodes. The equation of continuity governs the conduction of electric current through the stem, roots and soil. Application of this law is supported (1) by the linear arrangement of water-conducting elements (vessels and tracheids), as the main reason for electric anisotropy in living plant tissues; and (2) by the fact that the measurement of absorbing root surfaces occurs in the so-called close region of the electric field.

According to the equation of continuity for general electrically, conductive homogeneous and isotropic environments with a defined current source is given by:

$$div\vec{J} = \nabla * \vec{J} = 0 \qquad (8)$$

where $\vec{J}$ is current density, electric current flows by the shortest possible pathway from the external source through the stem sapwood into the main coarse root (and all roots connected to it), which is oriented in the direction of the current soil electrode. The current entering the whole stem and measured in the outer part of the electric circuit flows only through the given segment. Should any of the current flow through the other main coarse roots, it is taken into account by coefficient ζ in Equations 22 and 23.

If the soil current electrode C_2 is composed of a series of individual electrodes and is arranged in an arc covering the angle of, for instance, 60° (out of 360° of the total stem circumference), the electric current flows through all roots in a particular root segment in accordance with the Kirchhoff law. To estimate the absorbing root area for the whole tree, however, we have to include more root segments around the tree stem, or arrange the individual electrodes around the whole tree. Both current electrodes (C_1, C_2) have to be constructed in such a manner that their contact resistances (i.e., metal–soil and metal–wood) do not impact the measured current. That is, we have to reach the state when any further increase in number of individual electrodes does not increase the current, which can therefore be taken as the saturated current. We can simply apply multi-point electrodes (series of point electrodes) connected in parallel. For stems, a circumferential arrangement of current electrodes is best. Thus, current electrodes can, but need not, be arranged in an arc. The precondition is that the living woody tissues represent the biggest resistance in the circuit.

The important conclusion is, that we cannot directly measure absorbing root surfaces in whole large trees in a single operation, irrespective of whether we use several segments or a single segment. Exceptions to this rule are seedlings and young saplings, where the major roots are not yet developed and so we can measure all absorbing root surfaces for the whole tree simultaneously. We can, however, indirectly measure total absorbing root area of a large tree by the earth impedance method if we know the total number (N) of main coarse roots because we can get an approximation of total absorbing root area by multiplying the data measured in a single root segment by N. Alternatively, we can directly measure the absorption root surfaces of all main roots and sum the results. The possible presence of an anchoring root invisible on the soil surface can be taken into account by application of a special coefficient in Equation 7 and following Equations 22 and 23.

Measurement of resistivity of woody tissues

Classic electrotechnical methods can be applied in thin roots or stems with diameters of a few millimeters to estimate ρ_{wood}. In larger stems and roots, we have to apply methods that eliminate the contact resistance of metal electrodes. One approach can be applied to stems with diameters up to 16–18 cm and another for larger trees. The measurement of resistivity in medium-sized trees (Figures 5 and 6) is based on Equation 9:

$$R_{mn} = \rho_{wood} \frac{p}{s} \Rightarrow \rho_{wood} p = s\frac{U_{mn}}{I} \qquad (9)$$

when:

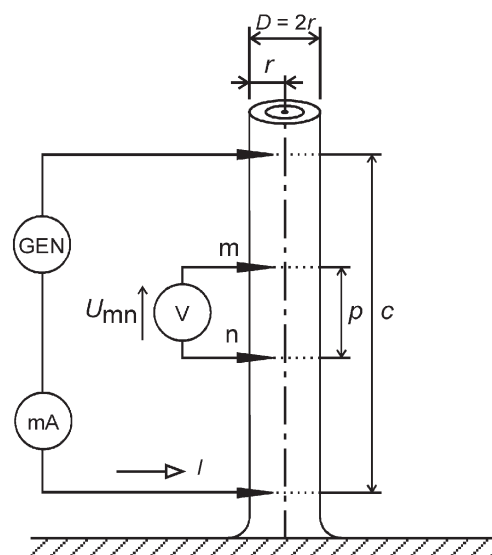$$s = \frac{\pi D^2}{4} \qquad (10)$$

the resistivity is:

Figure 5. Measurement of resistivity of woody tissue of trees with stem diameters up to 18 cm. Abbreviations: I = current; GEN = low frequency power supply; mA = milliammeter; V = voltmeter; U_{mn} = voltage drop between electrodes at points m and n; p = distance between potential electrodes at points m and n; c = distance between current electrodes; D = diameter; and r = radius.
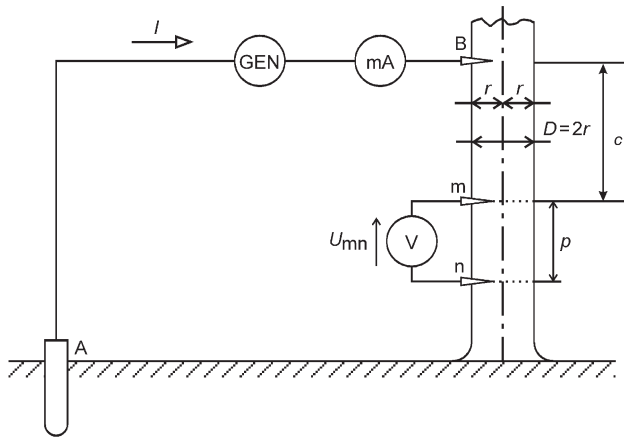
Figure 6. Measurement of resistivity of woody tissue of trees with stem diameters up to 18 cm. Abbreviations: GEN = low frequency power supply; mA = milliammeter; V = voltmeter; B = position of current electrode in the stem; A = position of current electrode in the soil; r = radius; D = diameter; U_{mn} = voltage drop between electrodes at points m and n; p = distance between potential electrodes at points m and n; and c = distance between current electrodes at position B and potential electrode at position m.

$$\rho_{wood} = \frac{\pi D^2 U_{mn}}{4\,pI} \qquad (11)$$

Measurement of ρ_{wood} in woody saplings is shown in Figure 7. It is important to keep the correct distances between electrodes, particularly $c > p$ and $c > D$. There is a pronounced difference between resistivity of sapwood and heartwood in many species and it appears to increase at the onset of the growing season (authors' unpublished observations). If we know sapwood depth (δ), we can calculate resistivity by the same circuit as shown in Figure 6:

$$\rho_{wood} = \frac{\pi(2\delta r - \delta^2)U_{mn}}{pI} \qquad (12)$$

where r is stem radius.

Because large trees with stem diameter $D = 2r > 30$ cm do not fulfill conditions of $c > D$, ρ_{wood} is estimated by resistance methods based on application of four electrodes $1 = C_1$, $2 = P_1$, $3 = P_2$, $4 = C_2$ inserted exactly one above another at distance a in the stem as shown in Figure 7. Both electrodes at the edge are current electrodes and are connected to an external source of voltage. The inner electrodes are potential electrodes and are connected to a voltmeter. Resistivity measured by this circuit is given by:

$$\rho_{wood} = \alpha\pi a\frac{U_{23}}{I} \qquad (13)$$

The dimensionless coefficient α is dependent on stem radius r and the insertion depth of the current electrodes h. Coefficient α describes the changes for the transition from a planar to a cylindrical boundary. The corresponding relationship is
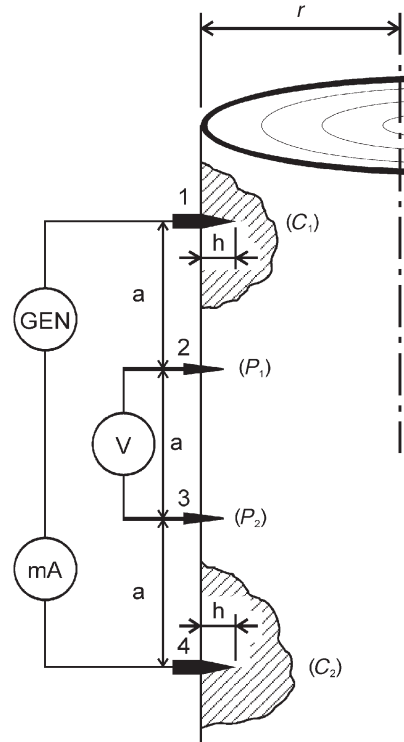

Figure 7. Measurement of resistivity of woody tissue of trees with stem diameters greater than 18 cm. Abbreviations: GEN = low frequency power supply; mA = milliammeter; V = voltmeter; a = distance of electrodes; r = radius; C_1 and C_2 = current electrodes in the stem; P_1 and P_2 = potential electrodes in the stem; and h = insertion depth of current electrodes.

shown in Figure 8. Equation 13 is derived from Figure 9 where we consider two homogeneous and isotropic environments (i.e., air and idealized living woody tissues (by ignoring their complex structure). A plane separates these environments. A metal electrode (M) is inserted into the woody tissue conducting current I. An electric current flows through the "woody half-space" in this case in the form of radial current filaments. The equipotential areas will be half-spheres with the center at the contact point of M with wood. The surface of the half-sphere with radius x is:

$$S = \frac{1}{2}4\pi x^2 = 2\pi x^2 \qquad (14)$$

Electrical resistance of the woody layer between the two concentric half-spheres x and dx is dR. Because we can write it for R in the form:

$$R = \rho_{wood}\frac{l}{S}$$

the elemental resistance will be dR:

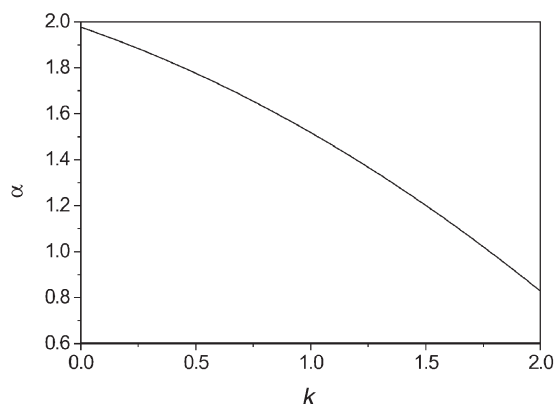$$dR = \rho_{wood}\frac{dx}{S} = \rho_{wood}\frac{dx}{2\pi x^2} \qquad (15)$$

Figure 8. Correction coefficient α for a cylindrical boundary on the ratio $k = h^2/D/2$, where h is the depth of electrode insertion and D is stem diameter.

The resistance of the half-sphere layer between the half-sphere with radius r_{12} and another half-sphere with radius r_{13} is:

$$R = \frac{\rho_{\text{wood}}}{2\pi} \int_{r_{12}}^{r_{13}} \frac{1}{x^2} dx = \frac{\rho_{\text{wood}}}{2\pi} \left(\frac{1}{r_{12}} \right) - \frac{1}{r_{13}} \qquad (16)$$

When we rearrange electrodes according to Figure 7, Equation 16 becomes:

$$R = \frac{U_{23}}{I} = \frac{\rho_{\text{wood}}}{2\pi} \left[\frac{1}{r_{12}} - \frac{1}{r_{13}} - \left(\frac{1}{r_{42}} - \frac{1}{r_{43}} \right) \right] \qquad (17)$$

When the electrodes are at the same distances a, we can write:

$$r_{12} = a, \ r_{13} = 2a, \ r_{43} = a, \ r_{42} = 2a \qquad (18)$$
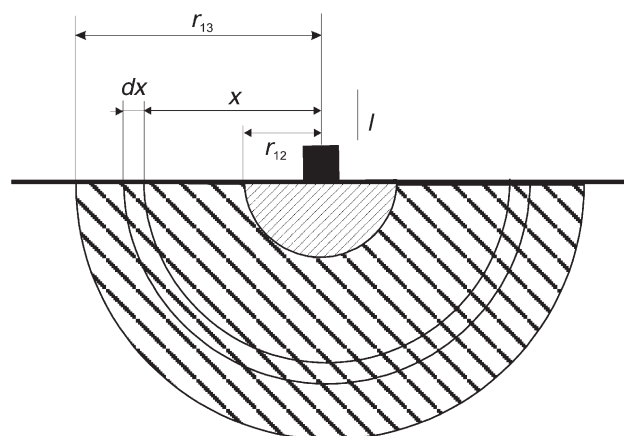
Equation 17 will then change to:

Figure 9. Derivation of the four-point method for measuring resistivity of large stems. Abbreviations: I = current; dx = infinitesimal element of variable x for integration; x = distance; r_{13} = radius of hemisphere in idealized woody tissue; and r_{12} = radius of idealized electrode.

$$R = \frac{\rho_{\text{wood}} U_{23}}{2\pi a I} \qquad (19)$$

The resistivity of the idealized woody tissue will be:

$$\rho_{\text{wood}} = 2\pi a R = 2\pi a \frac{U_{23}}{I} \qquad (20)$$

This relationship, known as the Wenner relationship, is applicable to the determination of unknown resistivity of any at least partially conductive woody half-sphere, separated from the air by a plane interface. However, stems of most woody species are cylindrical, which is why we have to apply Equation 20 rearranged into the form of Equation 13 in most cases (except for large stems). Both equations are equal if coefficient $\alpha = 2$ in Equation 13.

Mean resistivity at depth a and just below the stem surface is used in Equations 13 and 20. However, resistivity is heterogeneous across the stems as well as across stem sapwood, which is why, in larger stems, we should estimate resistivity as the mean of two or three distances between electrodes (and even different depths below the surface). The usual course of resistivity along the radius of a healthy stem is shown in Figure 10. Resistivity can be estimated by using a four-electrode approach in stems and also in main coarse roots providing that:

$$\alpha \leq \frac{D}{4} \qquad (21)$$
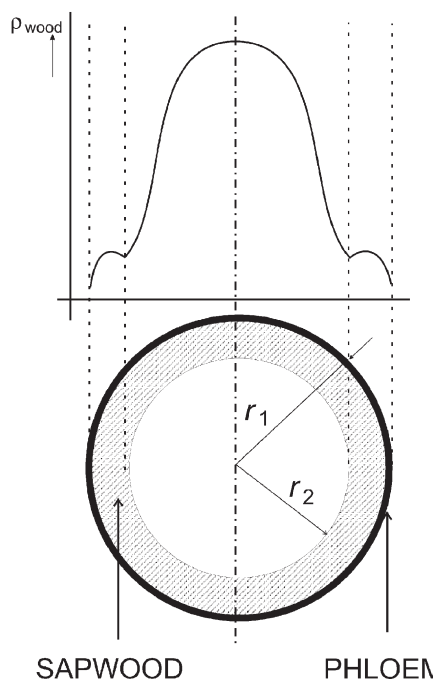
where D is stem or root diameter (including bark).

Figure 10. Dependence of resistivity on the radius of the stem. Abbreviations: ρ_{wood} = resistivity of wood; r_1 = radius of the stem; and r_2 = radius of the heartwood.

Measurement of absorbing root surfaces using discrete instrumentation

We choose the first (or final) segment and insert a set of current electrodes by which it is delimited. The measuring instruments are set up as shown in Figure 4. The potential electrode P_2 is gradually moved along the root segment radius in defined steps from the stem in the direction of current electrodes C_2 and the corresponding voltage is recorded. When we reach the beginning of the plateau, that is the interface between Sections I and II of the potential characteristic, we will know the required distance of L_{mean}. We then move the set of current electrodes C_2 to another root segment and repeat the measurement. We then measure woody tissue resistivity by one of the methods described above and insert the measured values into a modified form of Equation 7:

$$S_{AZ} = \frac{\rho_{wood} L_{mean} I}{U} \xi \eta \zeta \qquad (22)$$

The dimensionless coefficient ξ considers the effect called mutual electric shielding of roots. It causes a certain negative error in estimation of absorbing root surfaces. The dimensionless coefficient η considers the possible mechanical injury of roots and causes a positive error. Both coefficients are difficult to estimate exactly, but they are relatively small. The dimensionless coefficient ζ represents a negative error in estimation of absorbing root surfaces caused by electric current flowing through different pathways than those within the measured root segment (e.g., the small current flowing through other root segments). The values of both coefficients generally approximate 1.

Measurement of absorbing root surfaces using ratio-meters

We choose the first (or final) segment and insert a set of current electrodes by which it is delimited. The measuring instruments are set as shown in Figure 4. A ratio-meter is inserted into the circuit and its connectors arranged as shown in Figure 11. Electrode P_2 is moved in steps along root segment radius in the
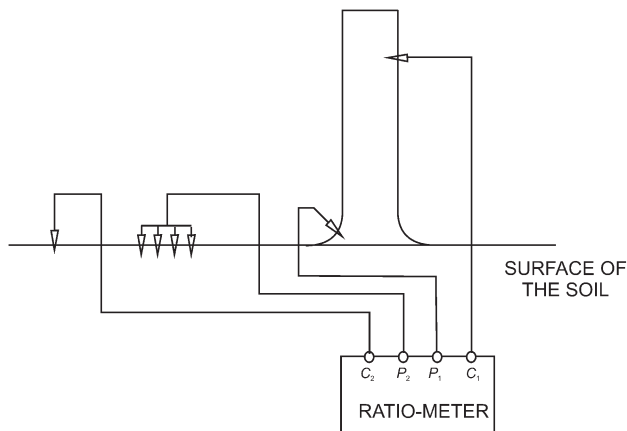

Figure 11. Scheme of logometric measurement. Abbreviations: C_1 and C_2 = electrodes of current circuit; and P_1 and P_2 = potential electrodes.

direction of electrodes C_2. The recorded values of resistance lie on the curve called surface hyperbole of the resistance conus. However, it has the same function and properties as the potential characteristic. We then estimate the interface between Sections I and II and, in this way, determine L_{mean} as described in the discrete instrumentation approach. Stem resistivity is measured as described in the discrete instrumentation approach. The measured values are inserted in Equation 23:

$$S_{AZ} = \frac{\rho_{wood} L_{mean}}{R_{rm}} \xi \eta \zeta \qquad (23)$$

where R_{rm} is the read out from the ratio-meter.

Conclusions

A new method for measuring absorbing root surfaces in trees based on a modification of the earth impedance method was developed and the soundness of its theoretical physical basis established. There are several different physical approaches applicable for the same purpose, but the approach described has been found suitable for trees of different sizes and species and can be applied under any field conditions. Verification of the method is presented in the accompanying paper.

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