Towards an effective characterization of root electrical properties: a spectroscopic approach

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Motivation

Background - The application of geophysical methods to root investigation is increasing in recent years because of the limitations associated with the use of traditional methods (root excavation, monoliths, minirhizotron etc.). Point sampling is only partially satisfactory as a result of the spatial variability and dynamics of the roots zone. Geophysical methods address these limitations by offering high resolution and non-invasive approaches to root investigation due to their ability to infer properties and structures of the subsurface as well as the flow and transport processes occurring in the shallow subsurface, at various spatial scales. Among various geophysical methods used for root studies, low frequency electrical methods are of great interest because they target direct electrical response of the roots. These methods have been applied in many cases with varying degree of successes but the problem of separating the root electrical response from the dominating influence of soil properties still exist.

Contribution - This work is aimed at studying the electrical properties (conduction and polarization) of roots at the segment scale (1-5 cm), to develop a suitable method for isolating the root electrical response from that of various soil properties.

Methods

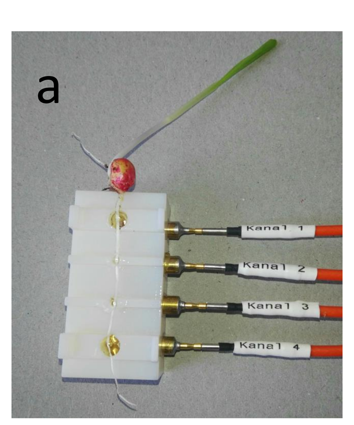
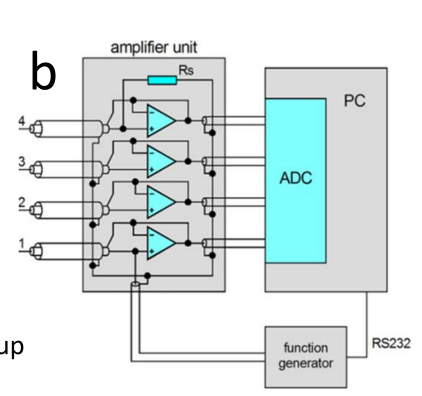


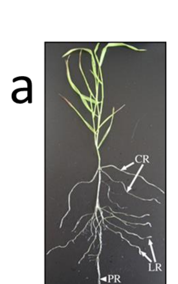
Figure 1. Measurement Set-up



Zimmermann et al. 2008

(a) Measurement set-up. The root is mounted on the sample holder, in a channel filled with conductivity gel. The electrodes are retracted from the channel such that contact with root is only established through the gel.

(b) Measurement system. It consists of amplifier unit, the function generator, data card and a computer.



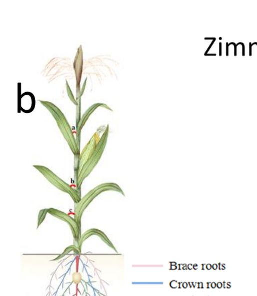


Figure 2. Test plants
(a) Brachypodium plant, composed of a primary root(PR), crown roots (CR) and lateral roots (LR) (Pacheco-Villalobos and Hardtke 2012)
(b) Maize plant, showing the roots in colour (Gong et al. 2015)

- Plants grown in sand to enable easier cleaning without water
- Total number of 32 plants were sampled (4*2*4)
- Root diameter measured with a digital calliper
- Measurement on primary roots close to root collar
- Root resistivity calculated using measured impedance and diameter

$$\rho_r = Z_r \frac{\pi D_r^2}{4L_r}$$

Results

Numerical correction of data

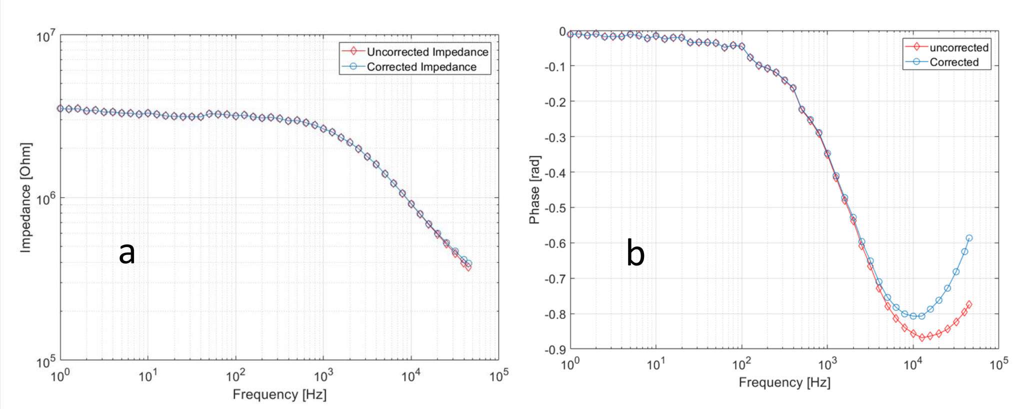


Figure 3. Numerical correction of a) impedance and b) phase data
(a) Corrected and uncorrected impedance data showing no variation.
(b) Corrected and uncorrected phase data.

- Phase value peaked at 0.87 rad before correction but reduced to 0.81 rad after the correction.
- The observed EM effect is 0.06 rad which is smaller than the polarization effect observed in the root.

Calibration and validation

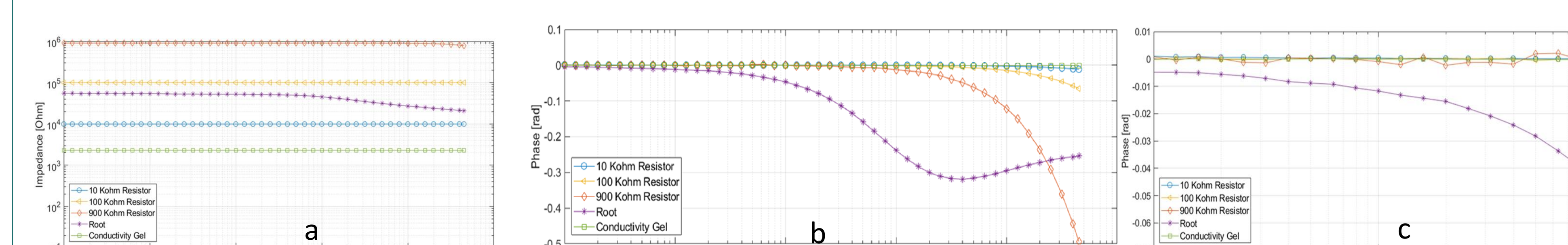


Figure 4. Validation of measurement set-up. (a) The impedance values of three ideal resistors and conductivity gel compared to that of the root. The measured impedances of the resistors matched their true values as expected but they exhibited the EM coupling effect at frequencies above 10 KHz. The root polarized strongly with a peak of 320 mrad, the conductivity gel showed a phase response of 1.2 mrad which is very small compared to that of the root. (c) Phase response at low frequencies below 100 Hz, showing a strong polarization response of the root at length scales.es. (b) The phase response of the resistors and conductivity gel compared to that of the root. The resistors showed no phase response.

Inter-species variability

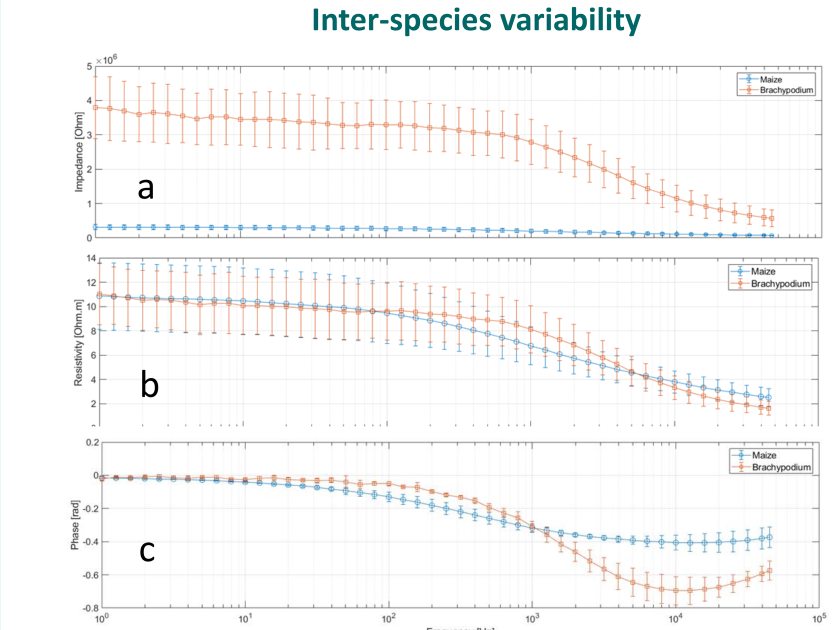


Figure 5. Inter-species variability. Comparing average electrical responses of several maize and brachipodium plant roots at 8 days.

(a) Average impedance of maize root compared to brachypodium root. Maize showed lower impedance (315 KΩ) with standard deviation of 74 KΩ, while that of brachipodium was higher (3.7 MΩ) with standard deviation of 0.9 MΩ.

(b) Resistivity values of both species showing only minor variations.

(c) Phase responses of both species

- Strong variation is observed between both species.
- Brachypodium roots polarized more strongly with a peak value of 700 mrad compared to maize root with a polarization peak value of 410 mrad.

Intra-species variability

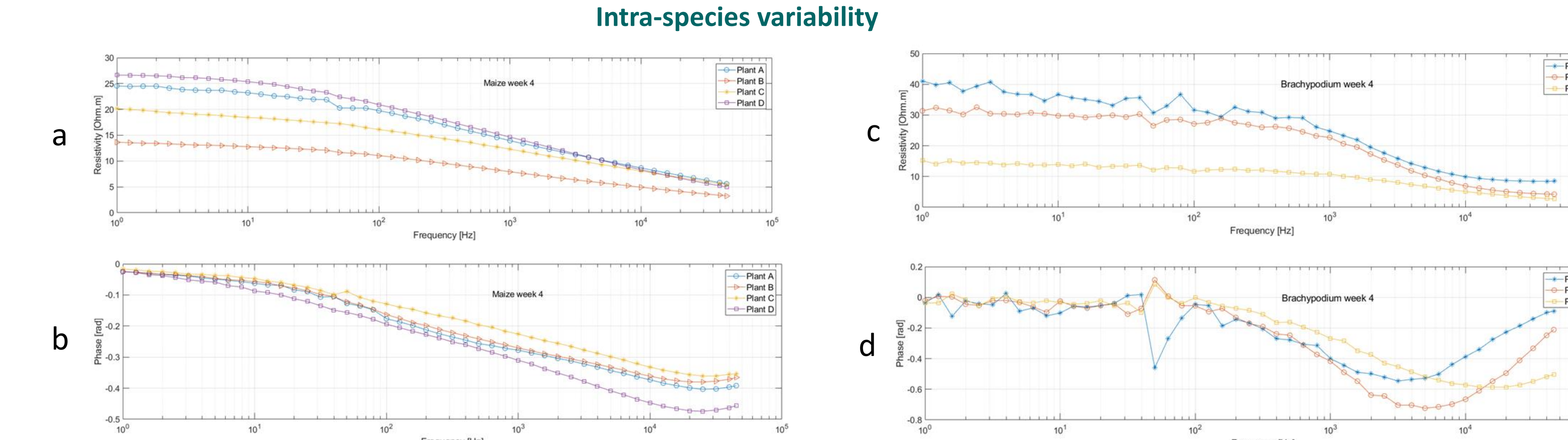
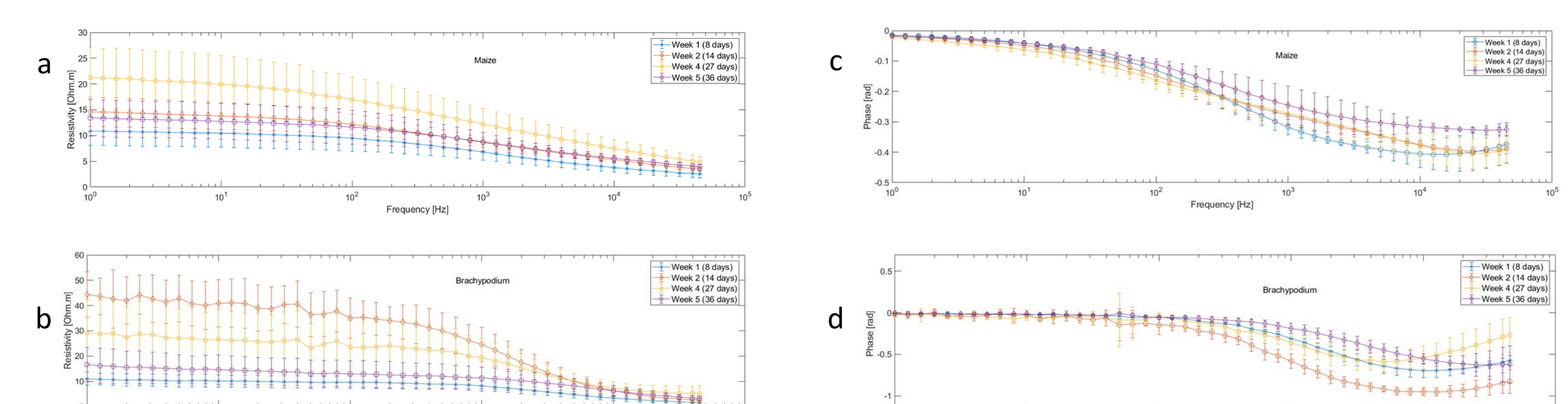


Figure 6. Intra-species variability. (a - b) The resistivity and phase responses of 4 maize plants (A, B, C and D) of same age (27 days) grown under same conditions are compared. They showed similar electrical signatures with minor variations. (c - d) The impedance, resistivity and phase responses of 3 different brachypodium plants (A, C and D) at 27 days, grown under same conditions are shown. They also show similar electrical signatures with minor variations.

Age effect on the root electrical response

Figure 7. Age effect on the electrical signals of maize and brachypodium roots.

(a - b) The effect of age on the electrical resistivity of maize and brachipodium roots.



(c - d) The effect of age on the phase responses of maize and brachypodium roots.

- Average response from different plants is shown here, with the error bars indicating the standard deviation.

Microscopic analysis of current pathways in roots

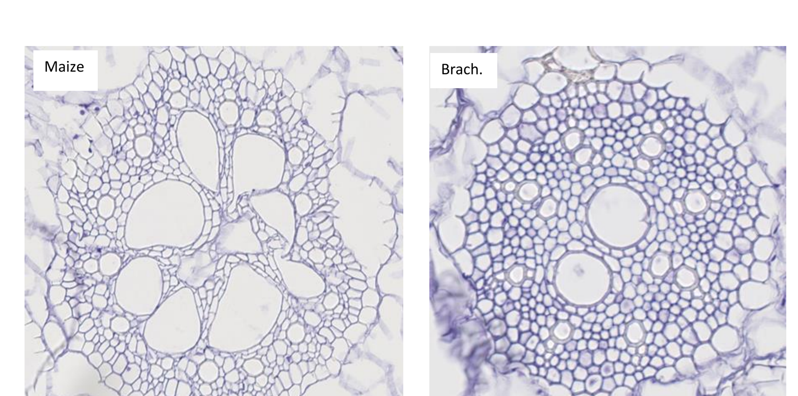


Figure 8. Microscopic section of Maize and Brachypodium primary roots at 24 days, sectioned at the maturation zone with the presence of root hairs.
- Brachypodium root is smaller in size with densely packed cortex cells
- Maize is larger in size, with cortex cells less densely packed

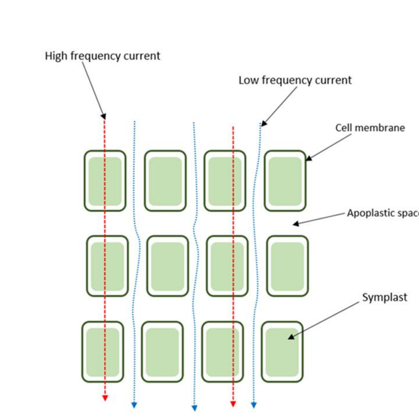


Figure 9. Current passage in roots at low and high frequencies. (see Bera et al. 2016 and Repo et al. 2012).

2-D model of root spectral IP response

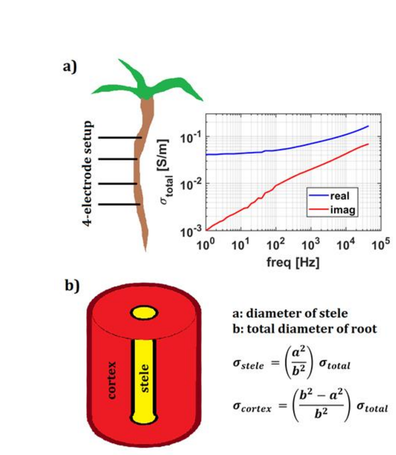


Figure 10. 2-layer model of root

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a) Schematic of IP measurement set up and measured maize root conductivity spectra.

b) Schematic of stele and cortex structure of a root segment and its conductivity formula. $\sigma stele$ and $\sigma cortext$ are the EC of stele and cortex parts of the root. σ $total$ is the spectra measured for intact root segments.

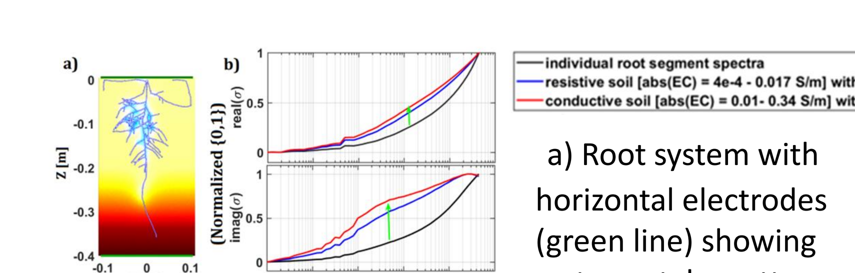

Figure 11. SIP response of roots in soil

a) Root system with horizontal electrodes (green line) showing water uptake pattern

b) Normalized effective conductivity (real and imaginary part) spectra for resistive soil (blue) and conductive soil (red) along with original root segment spectra (in black). The green arrow indicates a shift in spectra shape due to soil contrast.

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Conclusions

Intra- and Inter-species variability
- Different plants of each species studied showed similar response with minor variations.
- Maize and Brachypodium roots showed unique electrical signature which is largely dependent on their anatomy

Root properties
- Electrical response of roots depend mainly on their age and anatomy

Root differentiation from soils
- The polarization range for various earth materials fall within 0.2-20 mrad
- The results suggest that root segments can be differentiated from soils based mainly on their stronger polarization response
- Modeling result show that the imaginary part of conductivity is more effective in capturing key properties of different soil-root scenarios e.g. root age and soil wetness.

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