Imaging and characterization of crop root systems using electrical impedance tomography at the rhizotron scale

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A better understanding of root-soil interactions and associated processes is essential to achieve progress in crop breeding and management, prompting the need for high-resolution and non-destructive characterization methods. To date such methods are lacking, in particular for characterizing root growth and function in the field. A promising technique in this respect is electrical impedance tomography (EIT), which utilizes low-frequency electrical conduction and polarization properties of the subsurface in an imaging framework.

Crop roots are of non-woody nature and thus do not give raise to large resistivity contrasts in the subsurface. Therefore a more promising approach is the analysis of polarization signals originating within and in the direct vicinity of the roots. It is well established that cells and cell clusters exhibit polarization signals in alternative current fields due to the electrical double layer which forms at the cell membranes. However, upscaling of these signals to the scale of the whole root system is not trivial due to the complexity of the system and the occurrence of additional large-scale membranes such as the Casparian strip, which could be related to additional polarization responses. Moreover, the strength of the polarization originating at the surface of membranes is influenced by the charge concentrations on both sides of the double layer. This charge concentration is dominated by dissolved nutrients in root systems. Therefore a correlation between nutrient dynamics (uptake, usage, and translocation) and measured low-frequency polarization responses can be expected. In particular, the frequency peak of the low-frequency polarization response provides a link to the length scale at which the dominant polarization processes take place.

We investigated the capability of EIT to image crop root systems in a series of laboratory rhizotron experiments using canola plants grown in hydroponics. Those plants were then placed in a rhizotron container with a width of 30 cm, a height of 78 cm, and a depth of 2 cm, effectively providing a 2D environment for the experiment. The rhizotron was filled with tap water, which served two purposes: first, the root system could be visually mapped, and second, the low nutrient concentration in tap water created a stress situation for the plant system. This stress situation was then monitored using multi-frequency (450 mHz – 45 kHz) EIT measurements with the tomographic acquisition system EIT40 (Zimmermann et al. 2008) over a span of four days with a high temporal resolution (up to seven measurements per day). Corresponding EIT images for all frequencies were computed using the complex resistivity inversion code CRTomo (Kemna 2000). The complex resistivity spectra, as extracted for each of the image pixels, were then analyzed using a Debye decomposition scheme. Hereby the complex resistivity spectra $\rho^*(\omega)$ are described by a superposition of multiple Debye terms:

$$\rho^*(\omega) = \rho_0 \left[1 - \sum_{i=1}^{N} m_i \left(1 - \frac{1}{1 + j\omega\tau_i} \right) \right]$$

with j the imaginary number, ρ_0 the direct current resistivity, m_i the i-th chargeability value with the corresponding characteristic relaxation time τ_i. A total normalized chargeability:

$$m_{tot}^N = \frac{1}{\rho_0} \sum_{i=1}^{N} m_i$$

was computed, and the low-frequency peak relaxation time τ_{peak} of the resulting m distribution was used for further analysis.

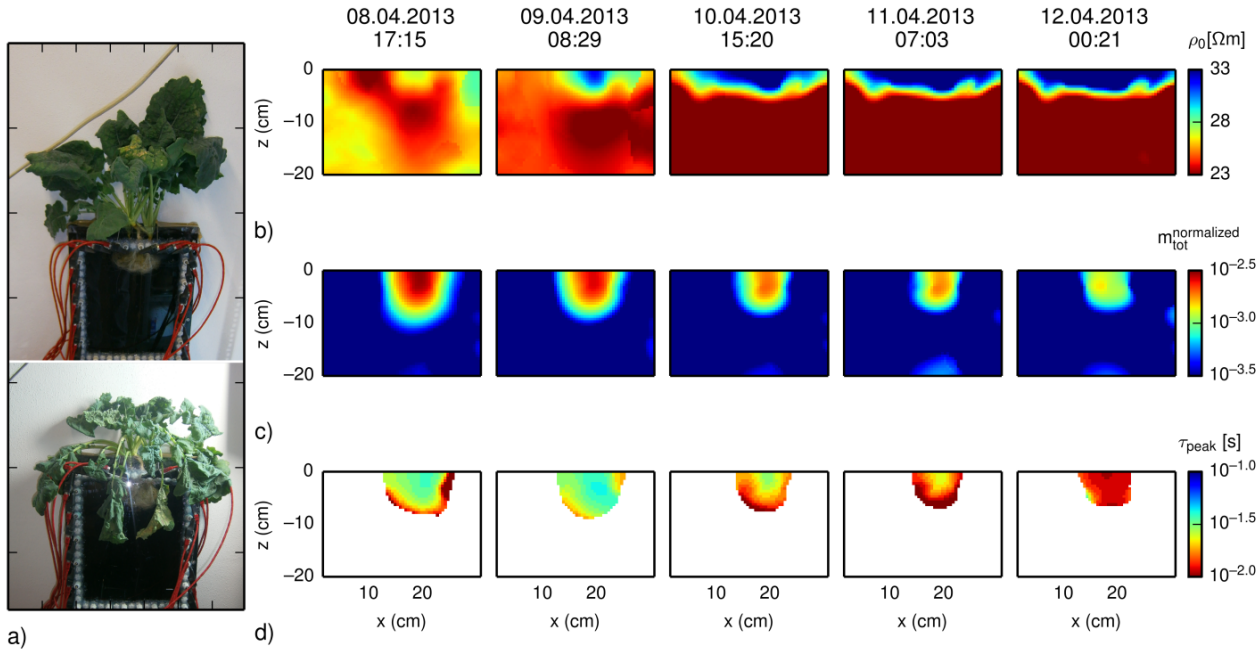

Fig. 1: EIT monitoring of multiple canola plant root systems in a nutrient stress situation over a span of four days. a) Picture of the plant system in the rhizotron at day one (top) and day four (bottom). b - d: Spectral parameters derived from a Debye decomposition of the complex resistivity pixel spectra extracted from imaging results; b) DC resistivity, c) total normalized chargeability, and d) low-frequency peak relaxation time.

As confirmed by visual inspection (Fig. 1a) the plant system reacted to the nutrient stress situation by dying back over the course of four days. Imaging results of the Debye decomposition are shown in Fig. 1b-d for selected time steps. As expected there are only small spatial and temporal changes in the resistivity (Fig. 1b). The emergence of a slightly more resistive zone at the top of the rhizotron does not coincide with the extension of the root system, and a more likely explanation is uptake of ions by the nutrient deprived root system. The total normalized chargeability (Fig. 1c) exhibits a good agreement with the root system's dimensions observed via photographs (Fig. 1a). Also, a steady decline in chargeability can be observed, which we assume corresponds to physiological processes within the root system given the nutrient deficit. The presented τ_{peak} results (Fig. 1d) can be interpreted as indicators of the dominant length scale at which polarization occurs; they show a slight, but steady, decline towards smaller values. This change in turn can either be interpreted as a breakdown of large-scale membranes such as the Casparian strip into smaller chunks, or as a change of the dominant polarization source as the membranes break down due to the nutrient deficit and the dieback of the root system.

The observed changes in relaxation time may serve as a means to characterize physiological processes within root systems, especially to study the response to stress situations. However, the present study only deals with a root system in water. If embedded in a soil matrix, the polarization response of the soil matrix will be superimposed on the root system's response, and further research is needed with regard to the discrimination of the sources of polarization in such an environment.

Nonetheless, our results demonstrate the capability of EIT to non-invasively image and monitor root systems at the rhizotron scale and suggest that EIT can be used as a tool for imaging, characterizing and monitoring crop roots at laboratory and field scales.

References

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