Multielectrode Geoelectrical Tomography for the Quantification of Plant Roots

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Abstract

The amount and spatial distribution of plant roots are crucial ecological features, and methods based on soil electrical resistivity (ρ) tomography (ERT) have been proposed for their non-destructive measurement. ERT allows to map root systems in conditions where the contrast of ρ between soil and roots is high, but the electrical behaviour of resistive or heterogeneous soils may interfere with root-borne effects and requires investigation.
We studied the spatial distribution of ρ in different soil-root conditions to test the hypothesis that ERT would allow to detect the spatial distribution of plant roots even when low contrast between roots and background soil variation was expected. High-resolution 2-D and 3-D DC (Direct Current) soil resistivity tomograms were used to compare areas of high and low vegetation density in containers where bare soil (LM), was compared to a *Medicago sativa* L. (HM) stand, and in resistive soils where a stand of *Arundo plinii* Turra (HA) was compared with a bare soil (LA) and the area under the canopy of *Olea europaea* L. (HO) was compared with interrow areas (LO). Destructive measurements of root biomass per unit soil volume (RD), soil electrical conductivity (EC), stone content (S) and water content (θ) were made in all treatments. Soil resistivity was significantly affected by vegetation density, with a resistive response in HM, HA and HO. The response was related to RD with significant univariate relationships and the spatial pattern of soil resistivity was dominated by roots and other resistive features like stones in all soils. This allows to conclude that ERT is able to detect plant-root effects even in the presence of a resistive background but resistive features interfere with the mesasurements and need to be taken into account.

Abbreviations: ρ = in-situ soil electrical resistivity; EC = electrical conductivity of soil samples; θ = volumetric water content; RD = root biomass per unit soil volume; ERT = electrical resistivity tomography; 2-D = Two-dimensional; 3-D = three-dimensional; DC = Direct Current.

Key-words: ERT, plant roots, spatial variability, soil resistivity.

Introduction

Electrical resistivity tomography is a technique suitable for the investigation of ground properties, based on the response of soil materials to the flux of electrical charges (Tabbagh et al., 2000) and its potential for measuring soil features relevant for agriculture has been explored mainly in relation to soil water and salinity, as well as the structural status of surface soil layers (Samouelian et al., 2005). Electrical resistivity (ρ) is a measure of the ability of a body to transfer electrical charges and in cylindrical geometry it may be defined as:

$$\rho = R\ (S/L)\ (\text{Ohm m})$$

where:
ρ = electrical resistivity
R = electrical resistance (Ohm)
S = cross-sectional area of the cylinder (m^2)
L = length of the cylinder (m).

Resistivity is the inverse of electrical conductivity (σ) and in geoelectrical surveys with

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galvanic methods it is measured through a "quadrupole": a set of minimum four conductors (electrodes). Two electrodes are used to apply electric currents to the soil (current electrodes) and the remaining two are needed to measure the resulting differences in electric potential in the soil (potential electrodes).

Different configurations of the quadrupole are possible: all electrodes may be placed on a line with potential electrodes between current electrodes (like in the Wenner array) or consecutive to them (like in the Dipole-dipole configuration). The resolution, sensitivity and depth of investigation are a function of the configuration and the distance between electrodes, as reviewed in Samouelian et al. (2005). The theoretical current flow for isotropic media is radial from the current electrodes into the soil and therefore equipotential lines are hemispherical.

Resistivity is therefore calculated from the differences in electrical potential (voltage) between the potential electrodes:

$$\rho = K\ (\Delta V/I)\ \text{(Ohm m)}$$

where:
ΔV= difference in electrical potential (V)
K = geometrical coefficient, depending on the electrode configuration
I = current intensity (A).

A single quadruple yields a single value of resistivity, attributed to a single soil volume with dimensions and depth defined by the spacing between electrodes and by the configuration used. A 2-D or 3-D tomography require multiple measurements, obtained through linear arrays of electrodes (for 2-D tomograms) or electrodes arranged in grids (for 3-D tomograms). The survey is conducted by measuring resistivity on a single quadrupole of the array at a time. Current injection and voltage recording are moved from a quadrupole to another along the line. All possible qaudrupole spacings along the line are used for measurements, starting from the lowest inter-elctrode spacing – corresponding to the distance between two adjacent electrodes – to maximum spacing, determined by the total length of the array. The distribution in space of voltage differences is a function of the different resistivity of soil volumes (Kearey et al., 2002).

In heterogeneous media the current flow lines are deformed and tend to be concentrated in conductive volumes. Therefore a distorted measurement is obtained based on the hypothesis of homogeneity, and a two-step procedure is necessary to obtain the correct spatial distribution of soil resistivity: ρ is first calculated according to the theoretical flow-line distribution in isotropic media, and is called "apparent resistivity" while the 2-D x-z section thus obtained is called pseudo-section. In order to obtain "real resistivity" values and to correctly place them in space a numerical modelling procedure is conducted for data inversion (Morelli and Labrecque, 1996). Resistivity values are thus attributed to the correct position after soil discretization in elementary cells. Resistivity data are then imaged in 2-D or 3-D tomograms (Fig. 1).

Plant tissues are made of anisotropic arrangements of conducting and insulating structures: the pathways for ion movement like the vascular system and the water-ion uptake paths conduct electrical charges whereas cell walls may be classified as equivalent to technical insulators of class II (Aubrecht et al., 2006). The electrical behavior is therefore highly variable within a plant organ and resistive regions prevail in lignified structures (Hagrey, 2007). This explainins the detection of resistive areas in the root zone of trees (Hagrey et al., 2004; Amato et al., 2008; Zenone et al., 2008). ERT has therefore been proposed as a method for the non-destructive measurement of plant roots (Hagrey, 2007). Zenone et al. (2008) found a qualitative correspondence between resistive features in 2-D and 3-D tomograms and tree roots in forest trees. Quantitative relations between root biomass of *Alnus glutinosa* (L.) and soil electrical resistivity have been found by Amato et al. (2008). Herbaceous roots provide less contrast with the background soil resistivity although significant relations have been reported by Amato et al. (2009) in a pot experiment, but the response of soil resistivity to increasing root biomass was of the same order of that due to variation in properties other than roots like soil texture or water. Also, the 3-D reconstruction of a pine tree root system in a sandy soil was possible through geoelectrical tomography with time-lapses at different water content only, since a single date of measurement was not enough to discriminate roots from other resistive features (Zenone et al., 2008). These

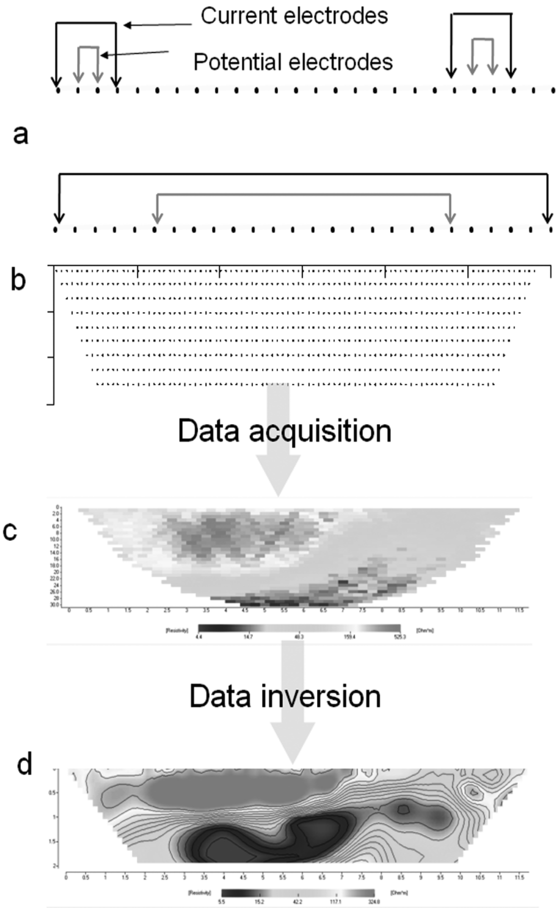

Figure 1. Resistivity tomography data acquisition and processing; a) liner array of electrodes with two quadrupoles at minimum spacing (top) and one quadrupole at maximum spacing (bottom). Dots represent electrodes; b) spatial distribution of soil volumes to which resistivity values are attributed based on the hypothesis of medium homogeneity in 2-D acquisition. Dots represent the center of each volume; c) 2-D pseudo-section of soil apparent resistivity obtained after data acquisition; d) 2-D section of soil resistivity obtained after data inversion with numerical modelling.

works suggest that the relation between root and soil resistivity is strongly dependent on the contrast between the resistivity of the background soil medium and that due to roots, and specifically possible problems arise in resistive soil materials like sand, or where a strong variability in resistivity is found in the soil matrix.

This study investigates the relations of roots and soil resistivity in a series of cases where a small contrast between roots and soil is expected in order to explore the limits of the applicability of ERT-based root detection methods.

Materials and methods

Data were collected in the month of July 2008 on three different experimental settings where high and low vegetation density treatments were compared as follows:

LM: unplanted soil in a container of 0.35x 0.44 m size with soil a silt loam soil (34.3% sand, 53% silt and 12.7% clay).

HM: soil in a container as above planted with *Medicago sativa* L. 76 days prior to measurements.

Containers were kept in growth chamber with a daily temperature of 25 ºC and night temperature of 22 ºC, and were irrigated daily to fully replace ET. Experimental details are described in Amato et al. (2009).

HA: a mature stand of Ar*undo plinii* Turra on a coastal sandy soil (98% sand) at Napoli (Italy).

LA: a soil with sparse vegetation adjacent to HA.

HO: an area under the canopy of 5 year-old *Olea europaea* L. at Cordoba (Spain) on a clay loam (33% clay, 35% silt, 32% sand).

LO: an area outside the canopy *Olea europaea* L. adjacent to HO.

In order to minimize the effect of water content on soil resistivity measurements were made in conditions where soil moisture was expected to be as uniform as possible, and namely the morning after a rainfall in Arundo, the morning after an evening irrigation in Medicago, and after several days without irrigation in Olea.

Two-dimensional DC resistivity tomography was performed in the field settings (HA, LA, HO and LO) and three-dimensional tomography in the container studies (HM and LM). All data was acquired with an Iris Syscal Pro ten-channel receiver (IRIS INSTRUMENTS, Orléans-France) resistivity meter. Two dimensional tomography was conducted on a linear soil transect using 48 electrodes spaced at 0.25 meters with dipole-dipole configuration (total length of transects = 11.75 m). The acquired dataset was processed with the Tomolab software (Geostudi Astier, Livorno, Italy) by a 2-D finite-element inversion algorithm (Morelli and LaBrecque, 1996) where the soil was divided into a rectangular mesh of cells of 0.125 m per side. A total of 1264 true-resisitivity values were obtained.

Three-dimensional DC resistivity tomography was performed in the LM and HM treatments inserting four arrays of electrodes in vertical holes placed at the vertices of a 0.2 – m square at the soil surface. Each array was made of electrodes spaced at 0.01 m. Holes were filled with a soil-water mud as contact material. An Iris Syscal Pro ten-channel receiver (IRIS INSTRUMENTS, Orléans-France) resistivity meter was used, and a dipole-dipoleConfiguration with 72 electrodes was adopted. Dipole-dipole configuration was selected, and full 3-D inversion was performed with the ERT-lab software (Geostudi Astier, Livorno, Italy-Multi-Phase Technologies LLC Sparks, NV) through a finite-element inversion algorithm to solve the forward modelling problem (Morelli and LaBrecque, 1996). The soil was divided into a cubic mesh of cells of 0.0025 m side with appropriate Dirichlet boundary conditions and the inversion procedure was based on a least squares smoothness constrained approach where noise is managed using a data weighting algorithm (LaBrecque et al., 1996) based on Occam's inversion (Constable et al., 1987). A total of 3096 resistivity values were obtained for each container, and the measured volume corresponded to a cube of 0.2 m side between the electrode arrays.

The depth of investigation was 0.2 m in the container and between 2 and 3 m in the field settings but data will be shown only up to the depth corresponding to destructive sampling (below).

Soil temperature was measured with T 105 thermoprobes inserted in the soil after acquisition outside the measured soil volume in order to avoid disturbance to subsequent sampling. Resistivity values were corrected for the effect of temperature, based on the temperature recorded at the closest thermoprobe depth for each resistivity value, and on the Campbell equation (Campbell et al., 1948), as suggested by Samouelian et al. (2005):

$$\rho = \rho T[1 + a(T - 25\ °C)]$$

where:

T = temperature

ρT = electrical resistivity measured at temperature T

ρ = electrical resistivity at the reference temperature of 25 °C

a = correction factor equal to 0.0202.

Soil sampling

Geo-electrical measurements took about 20 minutes after the insertion of electrodes and destructive soil samples were taken right after the completion of ERT.

In all experimental settings soil bulk density was determined by the cylinder method (Blake and Hartge, 1986) with a 98.175 cm3 internal volume on 4 replications. Resistivity data were processed in the field and the spatial distribution of ρ was used to drive destructive sampling. Soil cores were collected in order to cover a range of soil resistivity values in 0.1 m increments and up to the depth of 0.6 m in field settings and in 0.025 m increments and up to the depth of 0.2 m in the container experiment. Samples were weighed, and soil gravimetric water content was measured after drying at 110 °C. Soil electrical conductivity, soil texture (USDA method) and stone content (sieving on a 2 mm mesh sieve) were measured in the laboratory and root biomass was measured on the materials collected over a 0.2 mm square meshed sieve after clay dispersion with a 5% w:w solution of hexametaphosphate (85%) and sodium bicarbonate (15%) at 10% w/w dilution (Amato and Pardo, 1994). Non-root materials were separated manually from washed samples, and root materials were weighed after drying at 70 °C until constant weight. Soil gravimetric water content and root mass were divided by the dry mass of soil in each sample, and multiplied by the soil bulk density to yield volumetric water content (theta) and root dry mass per unit soil volume (RD).

Statistical analyses

Soil and root data were compared with soil resistivity values averaged over the volume corresponding to destructive soil samples location. T-tests and regression analysis were performed on resistivity data and soil-root variables.

Results and discussion

Two-dimensional tomographies from 2-D or 3-D acquisitions in all experimental settings are reported in Figure 2. Areas of high resistivity (red) are only or more frequently found in the high vegetation density treatments in all settings. Resistive areas under vegetation have been reported in a few cases (Panissod et al.,

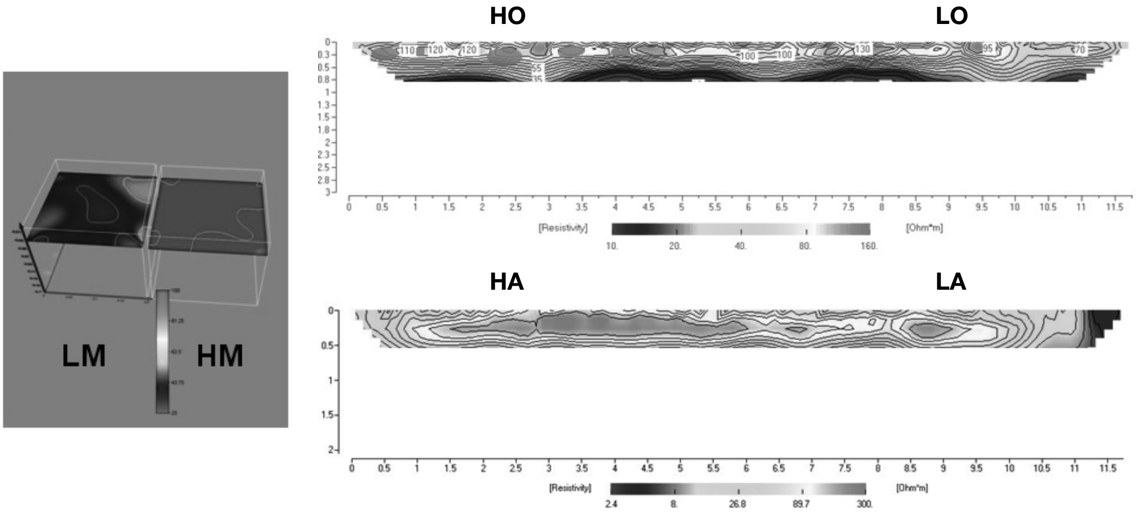

Figure 2. Two-dimensional sections at x = -0.03 m from a 3-D tomogram of soil resistivity for the container experiment (top), and from 2-D tomograms on the Olive experiment (middle) and the Arundo experiment (bottom). Labels indicate values of soil resistivity.

2001, Michot et al., 2003, Hagrey et al., 2004) and Hagrey (2007) raised the hypothesis that they could be related to plant roots. This was subsequently proven by Amato et al. (2008) and Zenone et al. (2008) for trees and Amato et al. (2009) for herbaceous roots. Nevertheless, other soil conditions related to the presence of vegetation like water content can affect soil resistivity (al Hagrey and Michaelsen, 2002), and also soil features independent of vegetation may produce a variation in ρ that risks to confound data interpretation as was found in sandy soil by Zenone et al. (2008). In our experiments average soil resistivity values for experimental treatments obtained from inversion of all data were up to 3 times higher in high density vegetation treatments (Fig. 3) and this corresponded to higher root biomass. Besides ρ and RD only EC for the olive experiment and stone content for the Arundo site deviated from the ratio value of 1, represented by the dashed line in Figure 3. Differences in ρ and RD between high and low density treatments were all highly significant ($P < 0.001$ – Tab. 1), whereas among other soil properties differences in EC in the olive setting were statistically significant, likely due to a higher salinity of the region under the tree canopy as a consequence of fertirrigation, and stone content was higher in the high vegetation density of the Arundo field.

In all settings univariate relationships between RD and ρ were found to be highly significant. With: RD = 4E-06ρ - 3E-05 ($R^2 = 0.56$) for HM data; RD = 5E-04ρ - 1.4E-02 ($R^2 = 0.42$) for the olive transect; RD = 2 E-04ρ - 5.7 E-03 ($R^2 = 0.46$) for the *Arundo* transect. Previous research on the effect of plant roots on soil resistivity was qualitative (Hagrey et al., 2004; Hagrey, 2007, Zenone et al., 2008) or quantitative with high values of R^2 in univariate relations be-

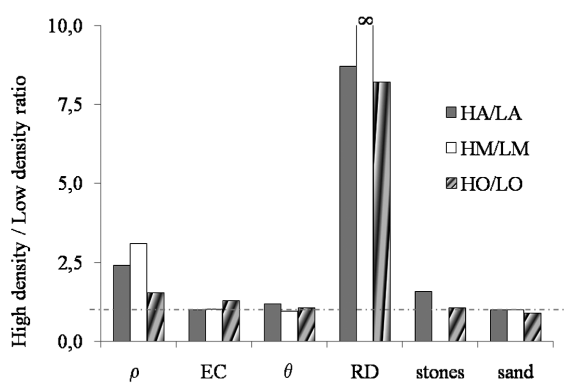

Figure 3. Ratio of values for soil and root properties in high vegetation density areas over low vegetation density areas: ρ = in-situ soil electrical resistivity; EC = electrical conductivity of soil samples; θ = volumetric water content RD = root biomass per unit soil volume; stones = soil particles collected on a 2 mm mesh sieve on the whole soil sample; sand: soil particles collected on a 2 mm mesh sieve on fine earth. The dashed line represents a ratio of 1.

Table 1. Soil and root properties in high and low vegetation density areas ρ = in-situ soil electrical resistivity; EC = 1:2 electrical conductivity of soil samples; θ = volumetric water content RD = root biomass per unit soil volume; stones = soil particles collected on a 2 mm mesh sieve on the whole soil sample; sand: soil particles collected on a 2 mm mesh sieve on fine earth. * = significantly different at $P < 0.05$; ** = significantly different at $P < 0.001$.

		ρ Ohm m	EC dS m^{-1}	θ m^3 m^{-3} %	RD Mg m^{-3}	Stones g g^{-1} %	Sand g g^{-1} %
Medicago							
LM	average	35,05721	0,2395	24,62032	0	0	34,3
	cv	23,4	14,1	8,2	0	0	3,2
HM	avergae	107,9806	0,2395	23,29956	0,00039	0	33,8
	cv	14,2	13,9	9,3	13,6	0	5,1
			**		**		
Arundo							
LA	average	48,52168	0,59	8,951877	0,00285	21,54391	98,1
	cv	102,8016	12,1	39,8975	107,5276	34,69814	2,4
HA	average	116,7544	0,58	10,62206	0,024794	34,04911	97,5
	cv	42,2693	13,4	33,11722	12,3989	21,98225	3,1
			**		**	**	
Olea							
LO	average	29,88391	0,21427	12,471	0,001127	27,42	35,15
	cv	84,1	16,9	21,4	121,5	35,1	4,7
HO	average	46,22802	0,27462	13,136	0,009266	29,134	31,539
	cv	61,3	24,1	25,5	56,8	32,7	10,1
			**	**	**		

tween ρ and RD Amato et al. (2008) in soil backgrounds of low resistivity and spatial variability. Nevertheles, when research was conducted on soils with resistive features like a high stone content or variations in sand content (Loperte et al., 2006; Lazzari et al., 2008; Amato et al., 2009) lower R^2 values were reported of the order of those found in our study. In our data from the container experiment no other factor was found to increase the amount of explained variance with a multiregressive approach, but in the field settings stones (in both sites) and EC (in the olive transect) were significantly introduced in multiple regression until the R^2 values reached 0.67 in olive and 0.72 in Arundo.

Soil electrical resistivity has been found to be a multivariate function of soil variables in general soil research (Samouelian et al., 2005) and in root research (Amato et al., 2009). The amount of variance in ρ explained by single properties depends on their effect on resistivity but also on the background soil resistivity and its spatial variation, so that in specific cases one or few factors may be found to dominate (Amato et al., 2009). In our study root density, stone content and EC had a significant effect on r but root biomass was always significantly related to ρ even where other features played a role. Soil water content did not show any significant relationship with ρ or any improvement in the coefficient of determination for multivariate relations in our experiments. Effects of soil water on resistivity are due to dissolved ions since the nature of the electric currents in soil is in large part electrolytic and therefore linked to the displacement of charges in pore-water (Samouelian et al., 2005). Therefore the relation of ρ and soil moisture is inverse, and the literature reports that soil water content is one of the most important soil variables affecting soil electrical resistivity in situ or its reciprocal, electrical conductivity (Archie, 1942; Hunt, 2004; Ewing and Hunt, 2006; Michot et al., 2003; Loperte et al., 2006; Hagrey, 2007; Amato et al., 2009). Nevertheless the amount of variability explained by soil water content in such studies is quite variable and may be remarkably reduced by the presence of soil factors that affect ρ more strongly or exhibit a larger variation than water (Amato et al., 2008; Amato et al., 2009). In some cases, therefore, no relationship or even a direct relationship has been reported and this has been discussed in terms of the masking effect of other soil properties (Amato et al., 2009).

Conclusions

Our results indicate that vegetation-related effects are able to modify the amount and spatial distribution of soil electrical resistivity with a resistive response in areas of high vegetation density compared to bare or less densely vegetated areas. This effect is detectable even in moderately resistive soils like sands and in the presence of soil variability in stone content and EC. In experimental settings with herbaceous and woody plants the resistive response was related to root biomass with significant univariate relationships and the spatial pattern of soil resistivity was dominated by roots in all soils but stones and EC were also significant. This allows to conclude that ERT is able to detect plant-root effects even when the contrast between roots and soils is expected to be low. Also, our results confirm that the quantitative relation of RD and ρ may provide a basis for the development of resistivity-founded methods for the non destructive spatial measurement of root mass *in-situ*, but other resistive features in the soil need to be taken into account.

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