ROOT WATER UPTAKE PATTERNS BY MICRO-ELECTRICAL RESISTIVITY TOMOGRAPHY

Daniela Vanella [1], Laura Busato [2], Jacopo Boaga [2], Simona Consoli [1]& Giorgio Cassiani [2]

(1) Dipartimento di Agricoltura, Alimentazione, Ambiente (Di3A), Università degli Studi di Catania, Via S. Sofia, 100 – 95123 Catania (Italy); (2) Dipartimento di Geoscienze, Università degli Studi di Padova, Via Gradenigo, 06 – 35131 Padova (Italy)

KEY POINTS

- *Micro three-dimensional electrical resistivity tomography to assess the differences between the portion of subsoil interested by the active root-zone of trees irrigated by different strategies (partial root drying and full irrigation).*
- *Time-lapse measurements conducted both with long-term periodicity and short-term repetition before and after irrigation highlighted the distribution of root water uptake zone both at shallow and larger depths.*
- *Ancillary information collected at the field site, e.g. trees physiological monitoring and meteorological data, allow to better explain the soil-plant-atmosphere dynamics that have take part at both irrigation plots.*

1 INTRODUCTION

Recently, the electrical resistivity tomography (ERT), also in three-dimension (3D-ERT), has been used to characterize root water uptake (RWU) and root system (e.g., *Cassiani et al.*, 2015 and references inside). The majority of the performed studies highlight the promising capabilities of the ERT technique, but the difficulties to interpret the measured electrical resistivity remain. First, as the resistivity is affected by several factors, the variability of these factors needs to be restricted or measured independently and a fitting calibration equation needs to be established (e.g., *Michot et al.*, 2003). Second, possibly rapid changes in the soil-plant-atmosphere continuum, such as a passing infiltration front after heavy rain, require high temporal resolution of the measurement to avoid temporal smearing (e.g., *Koestel et al.*, 2009). Finally, RWU processes are spatially variable and require at least decimetre resolution. Moreover moisture changes need to be at least 10% to be observed in time and space (*Michot et al.*, 2003).

The subsoil dynamics, particularly influenced by irrigation and RWU, have been characterized by the 3D ERT measurements coupled with plant transpiration through sap flow measurements. The specific objectives of the study were:

(a) to study the feasibility of a small scale monitoring of root zone processes using time-lapse 3D ERT;
(b) to assess the value of the data above for a first qualitative description of hydrological processes at the tens of centimetre scale.

2 MATERIALS AND METHODS

2.1 Experimental site

The study was conducted in an orange orchard (Citrus sinensis (L.) Osbeck) cv 'Tarocco Sciara' grafted on Carrizo citrange [Poncirus trifoliata (L.) Raf. × C. sinensis (L.) Osbeck], in Eastern Sicily (Italy) over the irrigation season 2015. 8-year~~s~~ old trees were planted at a spacing of 6 m x 4 m. The grove belongs to the Citrus and Mediterranean Crops Research Centre (CREA).

The climate of the area is semiarid Mediterranean with warm and dry summers. The meteorological data were collected at the experimental site by an automatic weather station and used to calculate the daily reference evapotranspiration (ET_0) through the Penman-Monteith equation (*Allen et al.*, 1998). The ET_0 was adjusted by the seasonal crop coefficient (K_c) for orange orchard (i.e., 0.7) in order to estimate the crop evapotranspiration (ET_c) and irrigation requirements. During June-October 2015 irrigation was scheduled weekly. The amount of water applied (three times per week) was measured with in-line water meters; water pressure regime was also checked by manometers. Different irrigation treatments were applied at the experimental field, an exhaustive description about those and the irrigation specs is in *Consoli et al.*, (2014). Herein we refer only to two irrigation treatments because they identify extremes conditions of water supply at the orange orchard site and they consist in:

(a) a control treatment (T1) where trees were irrigated with enough water to replace 100% ET_c;
(b) a partial root-zone drying treatment (T4) irrigated at 50% ET_c on one side of the root-zone while the

other side was kept dry.

The soil at the experimental field results fairly uniform with a sandy-loam texture and a percentage of organic matter of 1.25%. The mean water content at the field capacity (pF = 2.5) and wilting point (pF = 4.2) were 38.8% and 24.4%, respectively (*Consoli et al.*, 2014). The dynamic of soil water content distribution was recorded at the irrigation plots using dielectric soil moisture sensors (ECH2O probe, Decagon, Inc.) calibrated against gravimetric method.

2.2 Micro-electrical resistivity tomography monitoring

The micro-electrical resistivity tomography (3D-ERT) monitoring was carried out around two selected orange trees supplied by different irrigation techniques (i.e., full irrigation T1 and partial root drying, PRD T4). We designed a three-dimensional electrodes arrangement, which implies the usage of both superficial and buried electrodes. The ERT apparatus consisted on nine micro-boreholes (1.2 m depth) housing 12 electrodes each one (0.1 m spaced), plus ninth six surface electrodes (0.26 m spaced). The boreholes were spaced 1.3 m on a square grid, thus delimiting four quarters, one of which is centred on the considered tree (Figure 1).

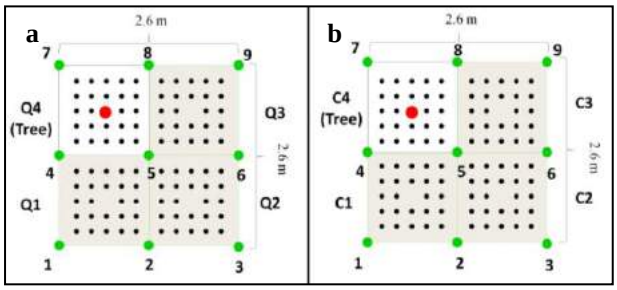

Figure 1. 3D-ERT monitoring scheme adopted at: a) partial root drying, PRD, T4 test plot and b) full irrigation, ET_c100%, T1. For each test plot (a and b), the scheme was composed of four quarters (Q1-Q2-Q3-Q4 and C1-C2-C3-C4). The trees in both plots (PRD and ET_c100%) insisted respectively on quarters Q4 and C4. The red circle represents the trees trunks; the green circles the boreholes; the black circles are the superficial electrodes.

The ERT monitoring was carried out with long-term periodicity during the irrigation season 2015 (June-September) and with short repetitions before and after irrigation at both test plots (T1 and T4). For the quarters where the trees insisted (Q4 and C4) we performed repetitions also contextually to the irrigation time. During the survey period we collected a total number of 50 dataset. Every dataset (quarter by quarter) was acquired adopting a complete skip 0 dipole-dipole scheme by a 10 channels resistivity meter (Syscal Pro 72 Switch, IRIS Instruments). We acquired both direct and reciprocal data to have an estimate of measurement errors (see e.g. *Binley et al.*, 1995). Every set of measures was processed using the same protocol that consisted in: assessment of the data quality; evaluation of the forward model errors; checking and averaging the duplicates measures; total inversion of the dataset considering all electrodes (buried and superficial) both in absolute and in time lapse mode by R3t code (*A. Binley*, Lancaster University); time lapse inversions of the quarters directly interested by the trees (Q4 and C4). The resistivity variations (%) at each time step were computed with respect to the background, considering in the time-lapse inversions only the same quadripoles. The effect of the temperature on the inverted imagery was ignored because the ERT monitoring was performed at the same time of the day during the summer season.

2.3 Sap flow measures

Water consumption at tree level was continuously measured by using the heat pulse velocity technique (HPV), (*Swanson & Whitfield*, 1981). For these measures, one 4 cm sap flow probe with two thermocouples embedded (Tranzflo NZ Ltd., Palmerston North, NZ) was inserted in the trunk of the tree. The temperature measurements were obtained by means of ultra-thin thermocouples that, one the probe is in place, are located at 5, and 15 mm within the trunk. Data of the probe were processed according to *Green et al.*, (2003) to integrate sap flow velocity over sapwood area and calculate transpiration. Four trees were selected to measure sap flow for the irrigation treatments (T1 and T4).

3 RESULTS AND DISCUSSION

The results of the geophysical monitoring carried out over the irrigation season 2015 at the experimental site, are herein described in qualitative terms for the treatments T1 and T4 (Figure 2).

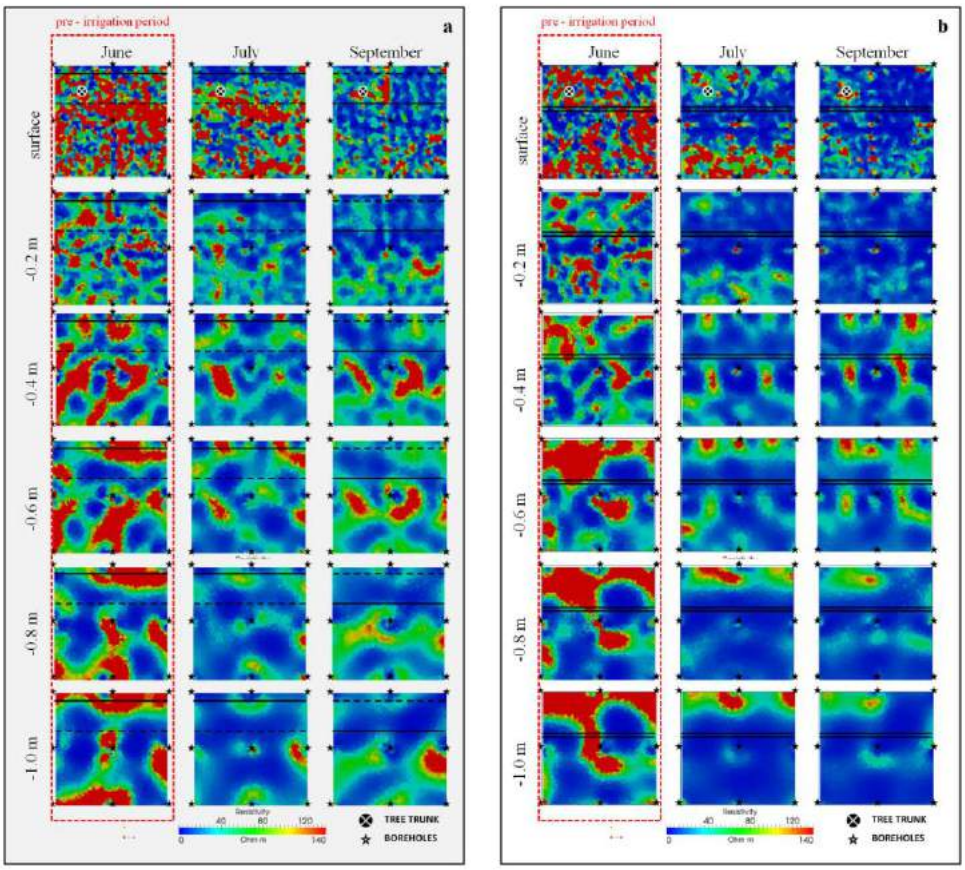

Figure 2. Absolute inversion of the background datasets collected during the ERT monitoring June-September 2015, a) at deficit irrigated test plot (PRD, T4); b) full irrigation test plot (T1). Imagery are sliced in function of the depth (from surface to -1.0 meters, every 0.2 meters). Resistivity values are expressed in Ohm m. Inversion error level was fixed at 16%. Active irrigation pipes are displayed with black solid lines.

The performance of the absolute model inversions (error level fixed at 10%) were evaluated in terms of number of iterations to achieve the solution, number of quadripoles considered in the inversions and final root mean square misfit. In general the solution was hard to solve. 2 dataset of June, 1 of July and 1 of September did not achieve the solution in 10 iterations. Moreover a great number of measures were rejected and then not taken into account in the inversion process, given the low resistance values and/or different polarity due to the electrode configuration adopted at the site. Another reason of the measures rejection could be the presence of soil cracks and gaps at the soil-root interface that are easily found around large structures and could also interrupt the flux of electrical current (*Carminati et al.*, 2009). Also the boreholes could interfere in the continuity between soil and electrodes. In order to obtain smoothed imagery the error of the inversion was increased to 16%. All datasets converged at this error level. Figure 2 illustrates the inverted images of the background collected during the irrigation season 2015 (June, July, September) at both test plots, i.e., a) PRD plot (T4) and b) full irrigated test plot (T1). Within the volume of investigated subsoil by the long term ERT monitoring, the resistivity images show significant differences in spatial and temporal terms. At both test plots, a decrease in resistivity values was observed from June to September 2015 in relation to the different degree of saturation of the soil due to the irrigation. Positive resistivity anomalies are reproduced during the investigated period at both test plots and at different depths. As no apparent soil texture differences characterize the two test plots, these variations might be attributed to the root distribution (*Rossi et al.*, 2011 and references inside). The resistivity changes could be related to the different answers of the active roots in function of irrigation period and irrigation type. In this survey, at the start of the irrigation

season (June 2015) greater resistivity anomalies were detected along the volume of investigated soil. At the mid and at the end of the irrigation season (July and September 2015) these resistivity anomalies in some cases migrated near the surface in proximity of the superficial emitters for both test plots. An example of time-lapse image for the quarter C4 is showed in Figure 3. It was obtained as the resistivity ratio between the resistance dataset collected at the end of the irrigation (2015, July 15th at 01:56 p.m.) and the background dataset acquired before the beginning of the irrigation the same day at 08:33 a.m.

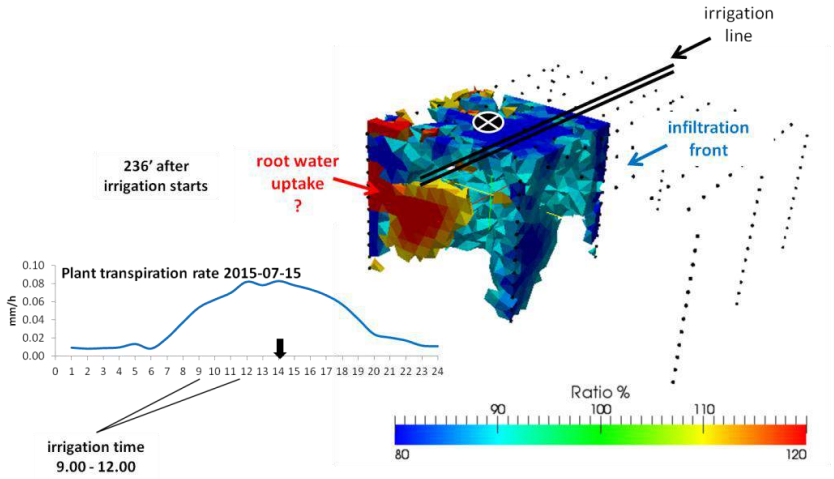

Figure 3. 3-D ERT image of resistivity change with respect to the background (initial condition) at a selected time instant (after irrigation ended). Tree transpiration rate (mm h^{-1}) and irrigation timing are displayed in the graph in function of time. Image refers to the full irrigated test plot (T1) on 15th July 2015.

The resistivity images may give useful information on the description of the sub-soil dynamics that occur in the root-zone of irrigated trees. However, the complexity and the heterogeneity of the system do not permit a clear explanation the processes related both to infiltration (irrigation) and RWU (tree transpiration), requiring integration between hydrological and geophysical modelling.

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