Time-lapse monitoring of root water uptake using electrical resistivity tomography and Mise-à-la-Masse: a vineyard infiltration experiment

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Abstract. This paper presents a time-lapse application of electrical methods (Electrical Resistivity Tomography – ERT – and Mise-à-la-Masse – MALM) for monitoring plant roots and their activity (root water uptake) during a controlled infiltration experiment. The use of non-invasive geophysical monitoring is of increasing interest as these techniques provide time-lapse imaging of processes that otherwise can only be measured at few specific spatial locations. The experiment here described was conducted in a vineyard in Bordeaux (France) and was focused on the behaviour of two neighbouring grapevines. The joint application of ERT and MALM has several advantages. While ERT in time-lapse mode is sensitive to changes in soil electrical resistivity and thus to the factors controlling it (mainly soil water content, in this context), MALM uses DC current injected in a tree stem to image where the plant-root system is in effective electrical contact with the soil at locations that are likely to be the same where root water uptake (RWU) takes place. Thus, ERT and MALM provide complementary information about the root structure and activity. The experiment shows that the region of likely electrical current sources produced by MALM does not change significantly during the infiltration time in spite of the strong changes of electrical resistivity caused by changes in soil water content. Ultimately, the interpretation of the current source distribution strengthened the hypothesis of using current as a proxy for root detection. This fact, together with the evidence that current injection in the soil and in the stem produce totally different voltage patterns, corroborates the idea that this application of MALM highlights the active root density in the soil. When considering the electrical resistivity changes (as measured by ERT) inside the stationary volume of active roots delineated by MALM, the overall tendency is towards a resistivity increase during irrigation time, which can be linked to a decrease in soil water content caused by root water uptake. On the contrary, when considering the soil volume outside the MALM-derived root water uptake region, the electrical resistivity tends to decrease as an effect of soil water content increase caused by the infiltration. The use of a simplified infiltration model confirms at least qualitatively this behaviour. The monitoring results are particularly promising, and the method can be applied to a variety of scales including the laboratory scale where direct evidence of roots structure and root water uptake can help corroborate the approach. Once fully validated, the joint use of MALM and ERT can be used as a valuable tool to study the activity of roots under a wide variety of field conditions.

1 Introduction

The interaction between soil and biota is one of the main mechanisms controlling the exchange of mass and energy between the Earth's terrestrial ecosystems and the atmosphere. Philip (1966) was the first to use the phrase "soil–plant–atmosphere continuum" (SPAC) to conceptualize this interface in the framework of continuum physics. Even though more than five decades have elapsed and many efforts have been expanded (e.g., Maxwell et al., 2007; de Arellano et al., 2012; Anderegg et al., 2013; Band et al., 2014), the current mechanistic understanding or modelling of SPAC is still unsatisfactory (e.g. Dirmeyer et al., 2006, 2014 and Newman et al., 2006). This is not totally surprising, since soil-plant interactions are complex, exhibiting scale- and species-dependence with high soil heterogeneity and plant growth plasticity. In this study, we focus on new methods designed to image root systems and their macroscopic functioning, in order to help understand the complex mechanisms of these systems (the rhizosphere, e.g. York et al., 2016). This diversity of interactions presents an enormous scientific challenge to understanding the linkages and chain of impacts (Richter and Mobley, 2009).

Roots contribute substantially to carbon sequestration. Roots are the connection between the soil, where water and nutrients reside, to the other organs and tissues of the plant, where these resources are used. Hence roots provide a link in the pathway for fluxes of soil water and other substances through the plant canopy to the atmosphere (e.g. Dawson and Stiegwolf, 2007). These transpiration fluxes are responsible for the largest fraction of water leaving the soil in vegetated systems (Chahine, 1992). Root Water uptake (RWU) influences the water dynamics in the rhizosphere (Couvreur et al., 2012) and the partitioning of net radiation into latent and sensible heat fluxes thereby impacting atmospheric boundary layer dynamics (Maxwell et al., 2007; de Arellano et al., 2012). Yet, a number of issues remain when representing RWU in both hydrological and atmospheric models. Dupuy et al. (2010) summarize the development of root growth models from its origins in the 1970s with simple spatial models (Hackett and Rose, 1972; Gerwitz and Page, 1974) to the development of very complex plant architectural models (Jourdan and Rey, 1997). Dupuy et al. (2010) advocate for a different approach, where roots systems are described as "density" distributions. Attempts in this direction (Dupuy et al., 2005; Draye et al., 2010; Dupuy and Vignes, 2012) require much less specific knowledge of the detailed mechanisms of meristem evolution, and yet are sufficient to describe the root "functions" in the framework of continuum physics, i.e. the one endorsed by the SPAC concept. These models also lend themselves more naturally to calibration against field evidence, as they focus on the "functioning" of roots, especially in terms of RWU (e.g. Volpe et al., 2013, Manoli et al., 2014). However, calibration requires that suitable data such as root density and soil water content evolution are available in a form comparable with the model to be calibrated. This is the main motivation behind the work presented herein.

A thorough understanding of root configuration in space and their evolution in time is impossible to achieve using only traditional invasive methods: this is particularly true for root hairs, i.e. for the absorptive unicellular extensions of epidermal cells of a root. These tiny, hair-like structures function as the major site of water and mineral uptake. Root hairs are extremely delicate, turn over quickly, and are subject to desiccation and easily destroyed. For these reasons, direct investigation of their in situ structure via excavation is practically impossible under field conditions.

The development of non-invasive or minimally invasive techniques is required to overcome the limitations of conventional invasive characterization approaches. Non-invasive methods are based on physical measurements at the boundary of the domain of interest, i.e. at the ground surface and, when possible, in shallow boreholes. Non-invasive methods provide spatially extensive, high-resolution information that can also be supported by more traditional local and more invasive data such as soil samples, TDR, lysimeters and rhizotron measurements.

Electrical signals may contribute to the detection of roots and to the characterization of their activities. For instance, self-potential (SP) signals can be associated with plant activities: water uptake generates a water circulation and a mineral segregation at the soil–roots interface that induce ionic concentration gradients which in turn generate voltages of the order of a few mV (Gibert et al., 2006). However, such SP sources are generally too low to be detectable in normally noisy environment. Induced Polarization (e.g. Kemna et al., 2012) is also a promising approach in root monitoring. This is consistent with the fact that root systems are commonly modelled as electrical circuits composed of resistance R and capacitance C (e.g. Dalton, 1995 and similar models). Recently, Mary et al. (2017) considered polarization from soil to root tissues, as well as the polarization processes along and around roots, to explain the phase shift (between injected current and voltage response) observed for different soil water content. Weigand and Kemna (2017, 2019) demonstrated that multi-frequency electrical impedance tomography is capable of imaging root systems extent.

In the investigation of roots and RWU the most widely used non-invasive technique is Electrical Resistivity Tomography (ERT – e.g. Binley and Kemna, 2005). ERT measures soil electrical resistivity and, in time-lapse mode, resistivity changes over time. Electrical resistivity values depend on soil type and its porosity, but also on state variables such as the saturation of electrolyte (water) in the pores, and the concentration of solutes in the pore water (as described e.g. by the classical Archie's law, 1942). Note, however, that other factors may play a role, such as clay content (Rhoades et al., 1976; Waxman and Smits, 1968) and temperature (e.g., Campbell et al., 1949). However, in general, it is possible to estimate water content changes from changes in electrical resistivity over time (and space) provided that pore water salinity does not vary dramatically. While ERT has been attempted for quantifying root biomass on herbaceous plants (e.g. Amato et al., 2009), the main use of this technique in this context aims at identifying changes in soil water content in space and evolution in time (e.g., Michot et al., 2003, 2016; Srayeddin and Doussan, 2009; Garré et al., 2011; Cassiani et al., 2012, Brillante et al. 2015). With specific reference to RWU, Cassiani et al. (2015, 2016), Consoli et al. (2017) and Vanella et al. (2018) used time-lapse ERT with 3D cross-hole configurations to monitor changes in soil electrical resistivity caused by irrigation and RWU for different crops (apple and citrus trees). It should also be noted that RWU and the release of different exudates by fine roots modify soil water content and resistivity at several temporal scales (York et al., 2016).

On the other hand, evidence suggests that roots themselves may produce signals in ERT surveys (Amato et al., 2008; Werban et al., 2008); however, these signals are often difficult to separate from soil heterogeneities and soil water content variations in space. Nevertheless, in most cases, the ranges of electrical resistivity of soil and roots overlap, and while the amplitude of contrasts varies according to the soil resistivity and tree species (e.g. Mary et al., 2016), the direct identification of root systems using ERT is often impractical.

Recently, the Mise-A-La-Masse (MALM) method has been proposed for plant root mapping. MALM is a classical electrical method (Parasnis, 1967) originally developed for mining exploration, but also used more recently e.g. in the context of landfill characterization (De Carlo et al., 2013) as well as conductive tracer test monitoring (Osiensky, 1997; Perri et al., 2018). In MALM, an electrical current is injected into a conductive body with a return current electrode far away ("at infinity"), and the resulting voltage is measured at the ground surface or in boreholes, again with a reference electrode at infinity: the shape of voltage contour lines is informative about the extent and orientation of the conductive body. This idea can be applied to the plant stem and roots system, considering that electrical current can be transmitted through the xylem and phloem (on either side of the cambium), where sap flow takes place. The main assumption is that fine root connections and mycorrhiza at the contact between roots and soil convey the injected current into the soil where this contact is efficient, thus appearing as a distribution of current sources in the ground. The location of these sources should correspond to the locations of active contacts between roots and soil, and could be identified starting from the measured voltage distribution at the ground surface or in boreholes. This approach has been recently tested by Mary et al. (2018, 2019) on vine trees and citrus trees, showing that current injection in the stem and in the soil just next to the stem produces very different voltage patterns, thus confirming that the stem-roots system conveys current differently from a direct injection in the ground.

In this study we present the results of an infiltration experiment conducted in a Bordeaux vineyard (France). This paper is meant to be an extension of Mary et al. (2018) and to focus on the results of an infiltration experiment. The experiment was monitored (also) using time-lapse 3D ERT and time-lapse MALM measurements, the latter performed by injecting current in the vine trees stems. This study had the following goals:

(a) define a non-invasive investigation protocol capable of "imaging" the root activity as well as the distribution of active roots, at least in terms of their continuum description mentioned above, under varying soil water content conditions;

(b) integrate the geophysical results with mass fluxes measurements in/out of the soil-plant continuum system using a simple 1D simulation reproducing the infiltration experiment.

(c) give recommendations for future experiments focusing on the method validation.

2 Methodology

2.1 Site description

The study was conducted in a commercial vineyard (Chateau La Louviere, Bordeaux) in the Pessac Leognan Appellation of France (long 44°44’15’’N, lat 0°34’45’’W). The climate of the region is oceanic with a mean annual air temperature of 13.7 °C and about 800 mm annual precipitation. Grapevine trees are planted at 1 m distance along the rows, and the rows are spaced about 1.5 m. We focused our interest on two neighbouring plants.

The vineyard is not irrigated. The soil is sandy down to 1 m depth with sandy clay below, down to 1.75 m, and calcareous at depth. Due to its larger particles and thus smaller surface area, the sandy layer has a relatively poor water retention capacity. Nevertheless, the water supply of the vine plant is not a limiting factor (refer to Fig. 2 and Mary et al. (2018) for more details about the plants and soil type). We concentrated our monitoring on only two neighbouring grapevines (Fig. 1), which differ in age and size: plant A was smaller and younger, plant B was considerably larger and older.

2.2 Meteorological measurements and irrigation schedule

Hourly meteorological data were acquired by an automatic weather station located about 300 m from the plot and managed by DEMETER (Agrometeorological Service - www.meteo-agriculture.eu/qui-sommes-nous/lhistoire-de-demeter). These micrometeorological data were valuable to estimate the initial soil conditions and the changes in time (Figure 2). Potential evapotranspiration (ETP) was computed according to the Penman-Monteith formula accounting for the incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall measured by the station. Prior to June 19, 2017, date of the first field data acquisition, little precipitation was recorded for 5 days (only 2.5mm on June 13) and only 18mm cumulative precipitation was recorded during the entire month of June 2017. The mean air temperature was very high (35°C under a well-ventilated shelter). Consequently, the plants were probably suffering from water deficit at the time of the experiment. Thus, at the start of the experiment, we assumed that the soil water content (SWC) around the plants was probably close to field capacity. As shown in Figure 2, the evapotranspiration rate was about 5.6 mm/day.

The controlled infiltration experiment was conducted using a sprinkler installed between the two monitored plants, placed at an elevation of 1.4m, in order to apply irrigation water as uniformly as possible. The irrigation started on June 19, 2017 at 13h00 and ended two hours later (15h00) for a total of 260 litres (104 l/h). Runoff was observed due to topography and probably induced more water supply for plant A that is located downhill. The irrigation water had an electrical conductivity of 720µS/cm at 15°C.

2.3 ERT and MALM data acquisition

We carried out a time-lapse ERT acquisition, based on custom-made ERT boreholes (six of them, each with 12 electrodes), plus surface electrodes (Fig. A1). The six boreholes were placed to form two equal rectangles at the ground surface. Each rectangle size was 1 m by 1.2m respectively in the row and inter-row line directions, with a vine tree placed at the centre of each rectangle. The boreholes were installed in June 2015 and a good electrical contact with soil was already achieved at the time of installation. The topmost electrode in each hole was 0.1 m below ground, with vertical electrode spacing along each borehole equal to 0.1 m. In each rectangle, 24 surface stainless steel electrodes (14mm diameter), spaced 20 cm in both horizontal directions, surrounded the plant stem arranged in a five by five regular mesh (with one skipped electrode near the stem). Note that after testing smaller electrodes size in surface, we finally adopted larger ones since they ensured a better contact in the loose soil and were heavier and more firmly grounded (3/cm) to resist irrigation. We conducted the acquisitions on each rectangle independently. Each acquisition was therefore performed using 72 electrodes (24 surface and 48 electrodes in 4 boreholes) using an IRIS Syscal Pro resistivity meter. For all measurements we used a skip 2 dipole-dipole acquisition (i.e., a configuration where the current dipoles and potential dipoles are three times larger than the minimal electrode spacing). The total dataset includes three types of measurements: 430 surface-to-surface, 2654 surface-to-borehole and 4026 in-hole measurements.

In addition to acquiring ERT data, we also acquired MALM data. MALM acquisition was logistically the same as ERT and was support by the same device, but used a pole-pole scheme (with two remote electrodes). Borehole and surface electrodes composing the measurement setup were used as potential electrodes, while current electrode C1 was planted directly into the stem, 10 cm from the soil surface, with an insertion depth of about 2 cm, in order to inject current directly into the cambium layer. The two remotes electrodes C2 (for current) and P2 (for voltage) were placed approximatively at 30m distance from the plot, in opposite directions. Note that for MALM (unlike than for ERT), one corner surface electrode was put near the stem in order to refine the information at the centre of each rectangle.

Each MALM acquisition was accompanied by a companion MALM acquisition where the current electrode C1 was placed directly in the soil next to the stem rather than in the stem itself. In this way the effect of the plant stem-root system in conveying current can be evidenced directly comparing the resulting voltage patterns resulting from the two MALM configurations.

For both ERT and MALM, we acquired both direct and reciprocal configurations (that swap current and voltage electrode pairs), in order to assess the reciprocal error as an estimate of measurement error (see e.g. Cassiani et al., 2006). Note that for the MALM case, reciprocals may not be the best solutions to estimate data quality as it has been shown in Mary et al. (2018), possibly because of non-linearity caused by current injection in the stem.

We adopted a time-lapse approach, conducting repeated ERT and MALM acquisitions over time in order to assess the evolution of the system's dynamics under changing moisture conditions associated with the infiltration experiment. We conducted repeated measurements starting on 19 June 2017 at 10:20 LT, and ending the next day at about 17:00 LT. The schedule of the acquisitions and the irrigation times is reported in Table 1.

2.4 Forward hydrological model and comparison with geophysical results

Hydrus 1D (Simunek, J. et al., 1998) was used to simulate cumulative infiltration and water content distributions for plant B (the larger one). The result from geophysical data acquisition were used to feed the hydrological model initial conditions. Boundary conditions were set for the column respectively as an atmospheric BC with surface run off (observed during the experiment) and triggered irrigation for the upper part, and free drainage for the lower part (see Figure 2). We assumed that the retention and hydraulic conductivity functions can be represented by the Mualem-van Genuchten model (MVG, Mualem, 1976; van Genuchten, 1980). Soil hydraulic parameters were directly inferred using grain size distribution and the pedo-transfer functions from the Rosetta software (Schaap et al., 2001). From the pit information (Mary et al., 2018), we assumed a uniform soil type along a 1D column ranging from 0 to 1.2m depth (Figure 2c). We used two types of time variable boundary conditions: (i) the irrigation rate changing with time, which was measured during the course of the experiment, and (ii) the potential evapotranspiration estimated according to meteorological data. We neglected direct evaporation. The root profile has been inferred from the MALM result at background (pre-irrigation) time using the average value along horizontal planes (Figure 2b). We used the functional form of RWU proposed by Feddes et al. (1978) with no water stress compensation and a non-uniform root profile between 0 and 0.7 m depth.

The link between the forward hydrological and the geophysical model is a petrophysical relation which transforms electrical resistivity distributions into the corresponding simulated water content (θ_{ERT}) distributions. There are several petrophysical models of varying complexity to relate water content with electrical resistivity (e.g. Archie, 1942; Waxman and Smits, 1968; Rhoades et al., 1976; Mualem and Friedman, 1991). We adopted Archie's approach: pore water conductivity was assumed equal to the electrical conductivity of the water used for the irrigation (720 µS/cm) for all the time steps. We considered homogenous soil distribution, so only one petrophysical relationship was necessary. Initial water content was inferred after transformation and reduction by averaging to 1D the ER values obtained during background time T_0. We obtained a non-homogeneous initial water content for the hydrological simulation varying from 0.1 to 0.27 cm3.cm-3 (Fig. 2a). In order to compare the model results with the geophysical data, we used control points at 0, 0.2, 0.4, 0.6, 0.8m depth.

2.5 Data analysis and processing

2.5.1 Micro-ERT time lapse analysis

The inversion of ERT data was conducted using the classical Occam's approach (Binley and Kemna, 2005). We conducted both absolute inversions and time-lapse resistivity inversions, as done in other papers (e.g. Cassiani et al., 2015, 2016). We used for inversion only the data that pass the 10% reciprocal error criterion at all measurement times. A large percentage of the data had reciprocity errors below this threshold. We inverted the data using the R3t code (Binley, 2019) adopting a 3-D mesh with very fine discretization between the boreholes, while larger elements were used for the outer zone. Most of the inversions converged after fewer than 5 iterations, and the final RMS errors respect the set convergence criteria (Table 1). For the time lapse inversion, we followed the procedure described e.g. in Cassiani et al. (2006) in order to get rid of systematic errors and highlight changes in term of percentage of ER ratios compare to the background time. Time-lapse inversions were run at a lower error level equal to 2% (consistently with the literature – e.g. Cassiani et al., 2006).

2.5.2 MALM modelling and source inversion

The MALM processing applied to a plant is thoroughly described in Mary et al (2018). Here we only recall the mathematical background on which the method relies on and some advances compare to the previous approach described by Mary et al. (2018).

In MALM, we measure the voltage V (with respect to the remote electrode) at N points, corresponding to the N electrodes locations, $x_1, x_2, \ldots, x_N$. Voltage depends on the density of current sources C according to Poisson's equation:

$$\nabla \cdot (\sigma \nabla V) = C \qquad (1)$$

where σ is the conductivity of the medium, here assumed to be defined by the conductivity distribution obtained from ERT data inversion. The main idea behind the source inversion is to identify the distribution of M current sources C(x,y,z) – in practice located at the mesh nodes $\boldsymbol{C}=[C_1, C_2, \ldots, C_M]$ – that produce the measured voltage V distribution in space. Given a distribution of current sources, and once σ(x,y,z) is known from ERT inversion, the forward problem is uniquely defined and consists in the calculation of the resulting V field. Conversely, the identification of C(x,y,z) distribution given V(x,y,z) and σ(x,y,z) is an ill-posed problem, that requires regularization and/or a priori assumptions in order to deliver stable results. Different approaches are possible – for a detailed analysis in this context see Mary et al. (2018). In this paper we have used the simplest approach, i.e. we assumed that one single current source was responsible for the entire voltage distribution. For each candidate location the sum of squares between computed and measured voltages was used as an index of misfit of that location as a possible MALM current source in the ground. Mary et al. (2018) introduced a simple index that can be mapped in the three-dimensional soil space and that measures the misfit that a specific location is the (single) current source generating the observed voltage field. This index (F_1) is defined as:

$$F_{1,i}(d, D_{f,i}) = \| d - D_{f,i} \|_2^2 \qquad (2)$$

Where d is a vector of measured voltage (normalised), and $D_{f,i}$ is a vector of modelled voltage corresponding to a single source injecting the entire known injected current at the i-th node in the mesh. The forward modelling producing the $D_{f,i}$ values is based on the direct solution of the DC current flow in a heterogeneous medium, such as implement in the R3t Finite Element code (Binley, 2019). Thus, the F_1 inversion accounts naturally for the heterogeneous electrical resistivity of the 3D soil volume, also in its evolution over time (e.g. as an effect of irrigation and RWU).

A more advanced objective function, which considers the presence of distributed sources, has also been introduced by Mary et al. (2018). Here we propose several important changes to that approach, on the basis of the work by Peruzzo et al. 2019 who proposed a linearized form of the problem. In this case, the cost function F_2 consists of error-weighted data misfit Φ_d and model roughness Φ_m containing model relative smallness and smoothness both weighted by the regularization parameter λ:

$$F_2 = \Phi_d + \lambda\Phi_m = W_\varepsilon \|d - f(m)\|_2^2 + \lambda(W_s \|m - m_0\|_2^2) \quad (3)$$

Given a set of N voltage measurements, minimization of the objective function, F_2, given by eq. (3), produces a vector of M current sources densities C_j (j = 1,2,…,M), where *d* is the data vector, $f(m)$ is the forward model that relates the model *m* to the resistances, W_s is a smoothness operator, W_ε is an error weighting matrix, and λ is a regularization parameter that determines the amount of smoothing imposed on *m* during the inversion. An L-curve analysis is used to identify the optimal regularisation parameter λ. In the revised algorithm all candidate current sources are kept during the inversion. Thus, there is no more a need to identify a threshold for which some sources are rejected. However, the misfit of F_1 is transformed into a normalized initial model (m_0) of current density via the inverse ($1/F_1$) transformation. During the inversion of the current density, we adopted a relative smallness regularisation as a prior criterion for the inversion i.e. the algorithm minimizes $\|m - m_0\|^2$, where m_0 is a reference model to which we believe the physical property distribution should be close.

3 Results

3.1 Background, irrigation time and monitoring of ERT measured data

The soil electrical conductivity during the period prior to irrigation (see ERT results in Figure 2b and 3a, respectively for plants A and B) ranged from 50 to 200 Ωm, with a median value around 100 Ωm, a range that is reasonable for a dry sandy soil. For plant A, the smaller plant, the highest resistivity values were distributed at about 0.5 m depth (Figure 2b). For the larger plant B (**Error! Reference source not found.**Figure 2a), the positive resistivity anomalies are more diffused and less resistive (150 Ω.m) compared to plant A, which reach larger depths. The very small-scale anomalies observed at the soil surface are likely to be caused by heterogeneous direct evaporation patterns or different soil compaction. More interesting are the resistive anomalies at intermediate depths. The background time (T_0) for both plants revealed a low resistive layer ranging in depth from 0 to 0.35 m for plant A and from 0 to 0.25 m for plant B. As observed in other case studies (e.g. Cassiani et al., 2015, 2016, Consoli et al., 2017; Vanella et al. 2018), these higher resistivity values are likely to be linked to soil saturation decrease caused by RWU, particularly in consideration of its intensity during this time of the year (June) for non-irrigated crops. Of course, we cannot fully exclude that higher resistivity is also related to woody roots presence, especially when they are dense. Besides, roots could also have induced soil swelling creating voids acting like resistive heterogeneities.

The T_1 time step was collected during the irrigation, at 2h for plant A and at 30 minutes for plant B after the beginning of the irrigation, so the variations of ER values are not directly comparable for the two plants. Figure shows the resistivity distribution during irrigation (at time step T_1) and after irrigation (T_2 to T_5) for plant B. The input of low resistivity water (15 Ωm, measured in laboratory) caused a homogeneous drop of the resistivity values (as much as 100 Ωm difference) around plant B. The observed resistivity decrease in the upper 40 cm can be attributed to the presence of a porous layer, and correspondingly fast infiltration. A similar drop can be seen for the plant A (Fig. B1). This is an indirect evidence that water infiltrated in both areas (that are next to each other) with no difference in soil hydraulic properties. For the time after irrigation, it is difficult to appreciate the change in resistivity from the absolute values while time-lapse inversion (Figure b) shows that the main increase in ER (up to 140% of the background value), was located in the upper layers (< 0.3m depth) and occurred between the background time and T_3. Note that the acquisition time T_3 corresponds to the morning of the following day, since no measurement were taken overnight, and the acquisition time match with the start of the increase of ET and mean air temperature. No increase was observed on plant A (Fig. B1). After T_3, no positive change in ER was observed.

3.2 Background and irrigation time steps of MALM measured data

Figure 5 shows the raw results of MALM acquisition on plant B, during background and irrigation, for both soil and stem injection configurations. Note that voltages are normalized against the corresponding injected current. For both surface and borehole electrodes the normalized voltage distribution can be compared against the one expected from the solution for a point injection of current I at the surface of a homogeneous soil of resistivity ρ :

$$V = \frac{I\rho}{2\pi r} \tag{4}$$

where r is the distance between the (surface) injection point and the point where voltage V is computed (see Fig.5e for a comparison). In all cases, both for surface and borehole electrodes, and both for stem and soil current injection, the voltage patterns are deformed with respect to the solution of Eq. (3) for a homogeneous soil. Some pieces of evidence are apparent from the raw data already:

a. In all cases, the pattern of surface and subsurface voltage is asymmetric with respect to the injection point (in the stem or close to it, in the soil) and thus different from the predictions of Eq. (3); this indicates that current pathways are controlled by the soil heterogeneous structure: note that at all times there is a clear indication that a conductive pathway extends from the plant to the right-upper corner of the image (this would be the classical use of MALM – identifying the shape of conductive bodies underground). Note that spatial variations of voltage between boreholes are consistent with surface observations i.e. the maximum voltage was measured on the borehole 4 located in the top right corner of the plot;

b. The voltage patterns in the case of stem injection are clearly different from the corresponding ones obtained from soil injection. In particular, injecting in the soil directly produces a stronger voltage signal both at the surface and in the boreholes than the corresponding voltage in the case of stem injection: this difference clearly points towards the fact that the plant-roots system must convey the current in a different way than the soil alone; tentatively the observed voltage features would indicate a deeper current injection in the case of stem injection. Looking at the qualitative differences between soil and stem injection in the borehole electrode data, the impact is very small at depths larger than 0.6m;

c. For both soil and stem injection, local anomalies observed in the background image are either removed or smoothed during the irrigation steps. The effect is equally pronounced in soil and stem injection, showing that this is caused essentially by the change in resistivity induced by the change in soil water content (see Fig.5).

Similar features are observed for plant A (results shown in appendix C1 and C2). The full-time monitoring is also shown only in appendix since a consistent and quantitative interpretation is not straightforward by a visual inspection of the raw MALM data.

3.3 Inversion of virtual current sources to estimate roots extents

Figure 6 shows the iso-surfaces of fitness index (or misfit) F_1 (Eq. 2) for the background (pre-irrigation) conditions of plant B (plant A in appendix C3) and for current injection in the soil and in the stem at all-time steps listed in Table 1. In all cases, Figure 6 shows the iso-surface corresponding to the value F_1= 7V corresponding to the 25% misfit index (value selected after analysing the evolution of the L-curve of sorted misfit F_1. The same threshold is fixed for all the time steps thus the images provide comparable information for all cases. Note, nevertheless, that the position of the active roots from one acquisition to the other during the irrigation experiment (or for different seasons) may vary, so the distribution of the misfit and ultimately the depth of the iso-surface describing active roots.

In particular, the F_1procedure highlights the remarkable difference, for both plants A and B, between the injection in the stem and in the soil. Current injection in the soil produces a voltage distribution that, albeit corresponding to a heterogeneous resistivity distribution and thus different from the predictions of a simpler model such as Eq. (3), collapses effectively to one point, i.e. the point where current was effectively injected in the ground. On the contrary, when current is injected in the stem, the region of possible source locations in the ground is much wider, and depicts a volume that is likely to correspond to the contact points between roots and soil, i.e. the volume where roots have an active role in the soil especially in terms of RWU. While this latter interpretation remains somewhat speculative, at least in the present experimental context, nevertheless the different results between soil and stem injection can only find an explanation in the role of roots and their spatial structure.

The most interesting feature shown by Figure 6 is that the likely source volumes do not change with time during irrigation except for the irrigation time T_1 for which the iso-surface extended slightly more at depth. Note that the F_1 procedure makes use of the changing electrical resistivity distributions caused by infiltrating water (see Fig.4) thus the result is not obvious, and indicates an underlying mechanism that is likely to be linked to the permanence of the roots structure over such a short time lapse.

Figure 7 shows the spatial distribution of the current density as an outcome of the minimisation of the F_2 function. Very similar observations to F_1 are driven from the current source density i.e. that current injection in the soil produces a current distribution collapses effectively to one point, i.e. the point where current was effectively injected in the ground, while when current is injected in the stem, the current distribution in the ground is much wider, and depicts a volume that is likely to correspond to the contact points between roots and soil. Note that for the different time steps (Fig. C4) did not highlight changes in the distribution of current density suggesting that the region of RWU was relatively constant during the experiment.

3.4 Electrical resistivity variations inside and outside the likely active roots zone

Our assumption is that the region identified by MALM F_1 for the background time corresponds to the RWU region. The inner area (IN) is then defined as the area within the closed iso-surface at the background time T_0. As the changes in the estimated extent of the root zone are only minor (Fig. 6), it makes sense to evaluate the changes, as an effect of irrigation, in electrical resistivity within such stable estimated root zone. Figure shows the ER variations of selected values in the zones inside and outside this estimated active root zone. It is apparent how irrigation causes a general decrease of electrical resistivity for both plants A (Fig. 8a) and B (Fig. 8b), and in both inner and outer regions. Note that even though the regions are different for the two plants, the behaviour is similar. Then at the end of irrigation we observe, for both plants, that resistivity continues to decrease outside the root active region, while it increases slightly inside. This behaviour is consistent with the fact that inside the region we expect that RWU progressively dries the soil, while outside this region resistivity continues to decrease (overall) as an effect (probably) of water redistribution in the unsaturated soil.

3.5 One-dimensional simulation of the infiltration

Figure 9a shows, the variations of the simulated soil water content (θ_{simu}) with time for control points located at different depths (see Fig. 2 for the geometry) and Fig. 9b shows the comparison against the 3dimensional variations of ER transformed values to soil water content (θ_{ERT}). Time steps of the ERT acquisition for starting time and end time are reported for an easier comparison between the two figures. At T_0, values of soil water content are about 0.1, a value close to field capacity for this type of soil, as previously assumed (section 2.2) and in agreement with the literature. Despite all the assumptions and models' limitation described later, the range of soil water seems also consistent between the simulation and the measured data. Note also that the dynamic is closely linked to the estimated ET and mean air temperature shown in Figure 2. The start and end time of the triggered irrigation are clearly identified respectively with a sharp increase following by a decrease of θ_{simu} at z=0, with a peak in SWC equal to 0.3. Between T_1 and T_2, only the upper surface (<0.2m depth) is affected by the irrigation front resulting in the increase of soil water content both visible in θ_{simu} and θ_{ERT} (Fig.9b). The infiltration front reaches the depth of 0.4 m during the collection of ERT data at time T_2. Time T_2 marks the starts of a regular decrease of the soil water content overnight in the top 40cm soil. Time T_3, coincident with an increasing ET and mean air temperature, highlights a rupture from a slow decrease to a higher decrease rate particularly for the soil surface (the layer <0.2m depth), in agreement with the observed changes in θ_{ERT} (Fig. 9b). Overall, Figure 9a and Figure 9b shows a good correlation between the dynamics of SWC changes predicted by the hydrological model (θ_{simu}) and observed via the ER transformed values (θ_{ERT}).

4 Discussion

The survey was carried out during a sunny summer season in a non-irrigated vineyard of the Bordeaux Region. The site is composed of sandy-loamy soil, thus there is a high infiltration rate during the experiment, and this would make it more difficult to distinguish RWU zones from infiltration zones as done for instance by Cassiani et al. (2015) using time-lapse ERT alone. The first objective of the study was to define a non-invasive investigation protocol capable of “imaging” the root activity as well as the distribution of active roots under varying soil water content. We demonstrated that the key additional information is provided by MALM which directly incorporates the ERT information in terms of changing electrical resistivity distribution in space including its evolution in time. MALM, and particularly its double application of current injection in the stem and in the soil next to it, uses electrical measurements in a totally different manner: here the plant-root system itself acts as a conductor, and the goal is to use the retrieved voltage distribution to infer where the current injected in the stem actually is conveyed into the soil: these locations are potentially the same locations where roots interact with the soil in terms of RWU. However, in order to try and locate the position of these points, it is necessary to know the soil electrical resistivity distribution at the time of measurements. At this scale of measurements, ERT provides 3D images of electrical resistivity distribution in the subsoil housing the root system. Fast acquisition allows the measurement of resistivity changes over time, which in turn can be linked to changes in SWC. This can be caused e.g. by water infiltration, or by RWU: in the latter case, negative SWC changes mapped through resistivity changes can be used to map the regions where roots exert an active suction and reduce SWC. However, water redistribution in the soil also plays a role in terms of resistivity changes. Thus some additional independent information about the location of active roots in the soil may help: this is the first coupling between ERT and MALM that has been integrated in the workflow. Considering the inverted MALM data as non-sensitive to soil water distribution has different potential useful impacts: the separation of contributions of root zone and outer area on ER values extracted from ERT help distinguish between soil processes such as RWU and hydraulic redistribution (hydraulic lift in particular).

Time-lapse ERT measurements gives clear evidence that injecting current in the stem and in the soil close to the stem produces different inversions even under changing soil water conditions. The soil injection produces a current density close to a punctual injection (located at the true single electrode location) whatever the soil water content. The stem injection helps identify a 3D region of likely distributed current injection locations, thus defining a region in the subsoil where RWU is likely to take place. The latter result is particularly useful, in perspective: when computing the time-lapse changes of electrical resistivity inside and outside this tentative RWU region during irrigation we clearly see that while inside resistivity increases (as an effect of RWU, as irrigation is still ongoing), outside resistivity decreases. Thus, our assumption that the region identified by MALM inversion (albeit very rough) corresponds to the RWU region is corroborated indirectly also by this evidence.

4.1 Comparison between geophysical data and hydrological model

A second objective of the study was to integrate the geophysical results a simple 1D model of the infiltration experiment, that takes into account the observed water fluxes. Dupuy et al., (2010) advocated the use of roots systems described as "density" distributions. We assimilated the root distribution, derived the geophysical data, into the hydrological model. Attempts in this direction are very promising to describe the root functioning in the framework of continuum physics, i.e. the one endorsed by SPAC. The integration of modelling and data has proven a key component of this type of hydro-geophysical studies, allowing us to draw quantitative results of practical interest. For example, in our study it is apparent that although infiltration occurred during the peak of evapotranspiration (between 1pm and 3pm), very small RWU was observed before the second day. Nevertheless, after a certain time, RWU is observed while infiltration is still ongoing. Smaller RWU observed for the small plant A compared to plant B is also observed.

4.2 Recommendation for future experiments

In this field case study, we had very little available quantitative information that could allow the validation of the geophysical data in terms of the volume of soil affected by RWU. The final objective of this study was then to discuss issues for obtaining suitable validation data using existing methods and propose some recommendation for future experiments:

(i) Validation through destructive methods has numerous potential pitfalls. As roots are underground, and thus invisible in their space-time evolution, and are also fragile, especially in their fine structure, the monitoring of their structure and activity using destructive methods such as trenches or air spade presents various limitations. In such approaches, even in the best case where fine roots may be sufficiently preserved and described, it is impossible to know where the active roots actually are. Active roots may be located only in one part of the whole root system. Destructive methods may help to validate the confidence area determined by F_1 but are not appropriated methods to validate the F_2 inversion.

(ii) We recommend the use of traditional methods (such as Time Domain Reflectometry-TDR and tensiometers) for future studies. Though punctual, these data can greatly facilitate the data calibration and validation of geophysical methods.

Finally, more research needs to be conducted to understand how MALM can provide information to be correlated with the actual RWU and thus to the estimated transpiration. The study of complex root-soil interactions requires that high time resolution and extensive data are collected and processed. In order to quantitively evaluate RWU using the variations of ER, many more data instants per day must be acquired. In this study, we only used ERT and MALM information to initialize the infiltration model, and only a qualitative comparison was conducted between model predictions and geophysical results. In the next future, a real assimilation scheme using data assimilation technique should be adopted.

5 Conclusions

This study presents an approach to define the extent of active roots distribution using non-invasive investigations, and thus particularly suitable to be applied under real field conditions. We applied a mix of ERT and MALM techniques, using the same electrode and surface electrode distribution. The power of the approach lies in the complementary capabilities of the two techniques in providing information concerning the root structure and activity. The approach has been tested in a vineyard during an irrigation experiment. Future experiments would require that high time resolution extensive data are collected, and the results are analysed in conjunction with data from traditional monitoring methods in order to qualitatively integrate geophysical results into a hydrological one. The presented approach can be easily replicated under a variety of conditions, as DC electrical methods such as ERT and MALM do not possess a spatial scaling per se, but their resolution depends on electrode spacing as well as on other factors that are difficult to assess a priori, such as resistivity contrasts and signal to noise ratio. Thus similar experiments can also be used in the laboratory, where more direct evidence of root distribution can be used to further validate the method.

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Data availability

Data used to generate the figures can be accessed on the Padua Research Archive (Link to come after decision).

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Table 1: schedule of the acquisitions and the irrigation times; Plant A and B are measured consecutively and consist each time of three measurements: ERT, MALM stem and MALM soil. Assessment of data and inversion quality from the two last columns i.e. respectively data kept after reciprocal analysis at 10% and RMS error at the end of the inversion.

Acquisition no.	**Plant**	**Starting time (LT)**	**Ending time (LT)**	**Irrigation**	**Date**	**Nb of data inverted (10 % reciprocals)**	**Final RMS (Ohm.m)**
0 (background)	A	10:20	11:00		Day 1 (19 June 2017)	1614	1.15
	B	12:20	13:00			1926	1.76
1 (Irrigation)	A	15:00	15:30	13h00 to 15h30, 104lh-1 For both plants		1277	1.54
	B	13:30	14:00			1721	1.31
2	A	17:00	17:30			1747	1.36
	B	18:00	18.45			1459	1.50
3	A	10:30	11:00		Day 2	1516	1.72
	B	9:30	10:00			2048	1.24
4	A	14:00	14:30			1835	1.38
	B	15:00	15:30			2029	1.53
5	A	18:00	18:30			1780	1.23
	B	17:00	17:30			1990	1.28

Figure 1: picture of the field site in May 2017 (a) wired plants investigated (b) and grape status during the experiment in June 2017 (c)

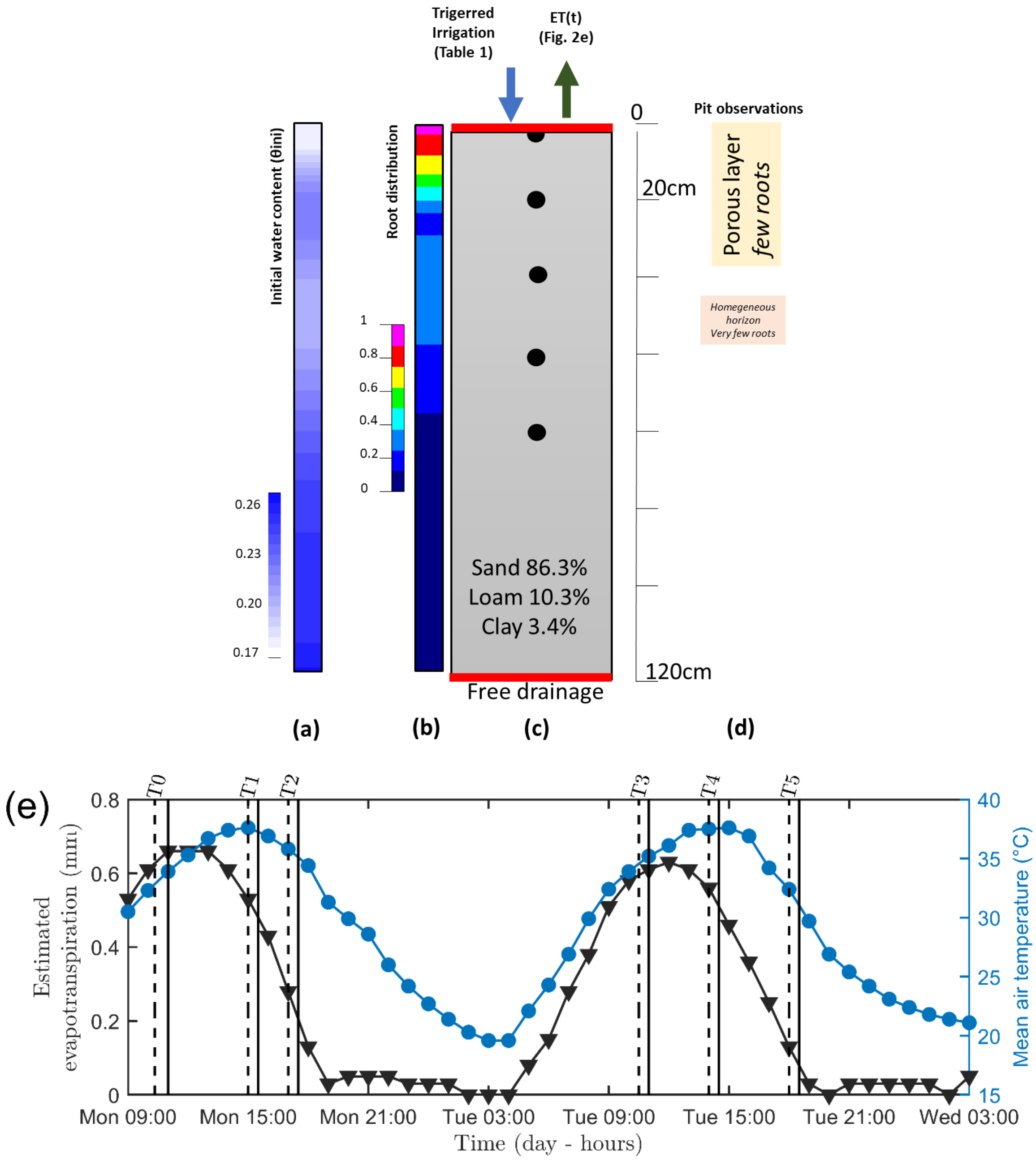


Figure 2: Initial (a,b,c) and time varying atmospheric conditions (e) used the hydrological simulation (e). From left to right (a-d), initial conditions on soil water content θ_{ini}, root density (1/cm), soil type, and pit observations. (e) variation of temperature (blue line) and estimated evapotranspiration (black line) derived from a nearby meteorological station. The vertical lines indicate acquisition times for plant A (dashed and plain line respectively for the start and the end of the measurement, see Table 1).

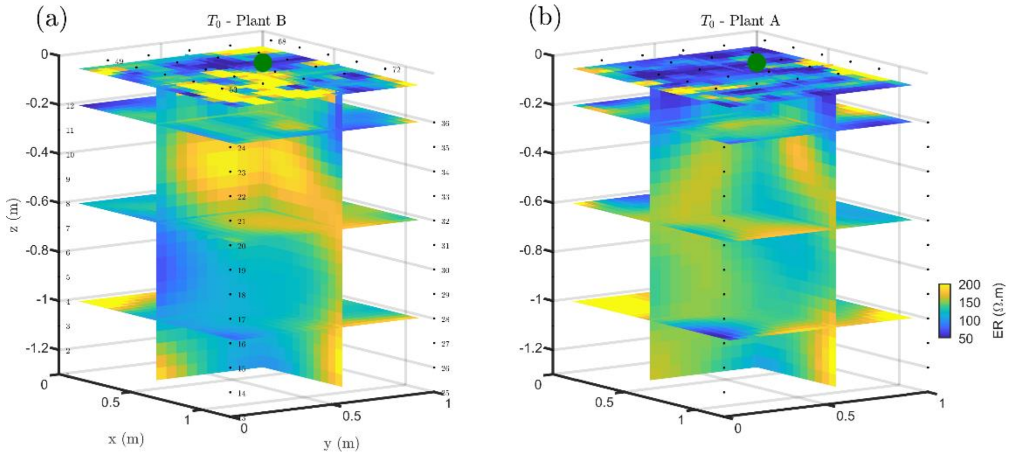


Figure 3: Results of the 3-D ERT inversion for the background time T_0 for plant A (b) and A (b). 3-D resistivity volume (log scale) sliced at the tree stem position (vertically) and at four depths (0.05, 0.2 0.6 and 1m), with the green point showing the location of the plant stem.

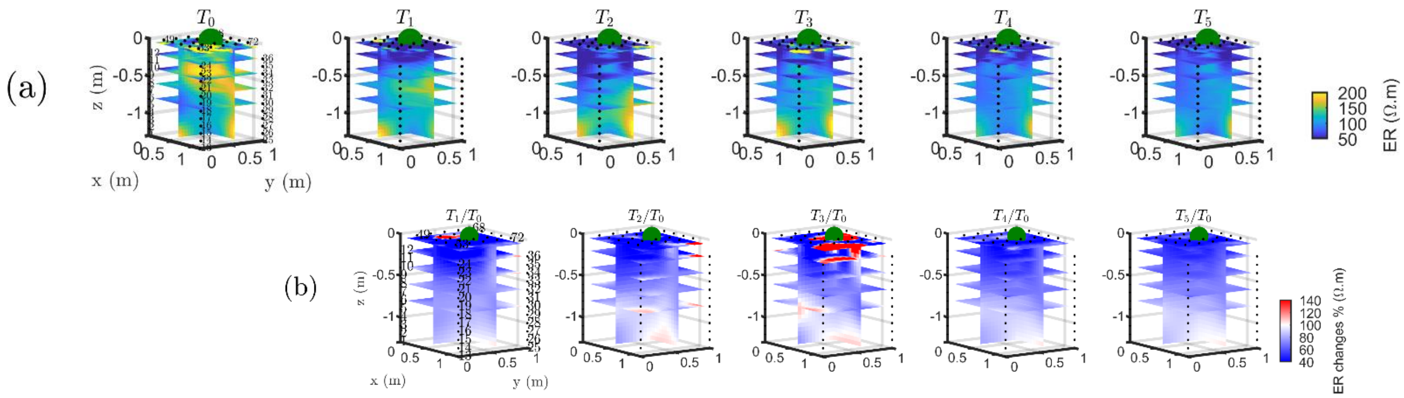


Figure 4: 3D ERT results for plant B (plant A, in appendix Fig. B1). The volume is sliced at the tree stem position (vertically) and at five depths (0.05, 0.2, 0,4, 0.6 and 0.8 m). (a) 3D inversion of the resistivity (in Ωm, log scale) from the background time T_0, during irrigation T_1 and after irrigation. (b) time-lapse inversion (following Cassiani et al., 2006) showing the ratios (in % of ER changes) between time step T_i and background time T_0 (100% in white means no change).

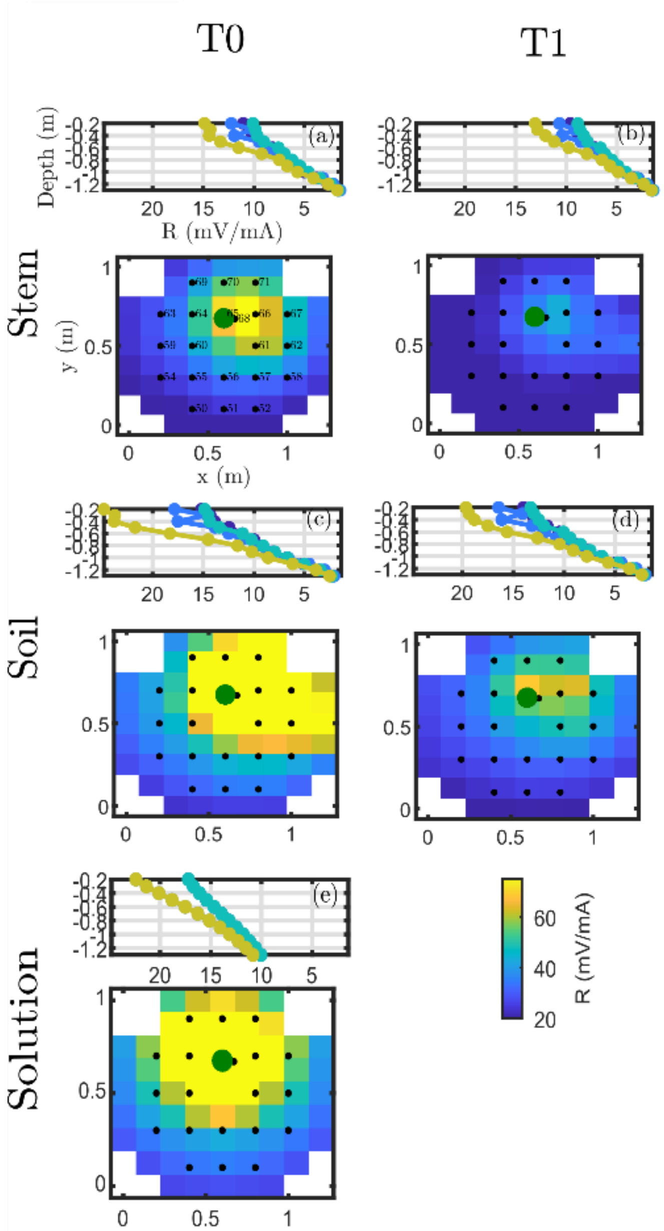


Figure 5: plant A, MALM results showing variations in surface (horizontal plan) of resistance R (in mV/mA) for the initial state background T_0 (a,c) and irrigation T_1 (b,d) time steps. Comparison between the stem injection (a,b) and soil injection (c,d). The black points show the surface electrodes location. The green point shows the positions of the plant stem. Data are filtered using a threshold on reciprocal acquisition of 20%. (e) shows the solution using eq. (2) for a homogeneous soil of 100 Ohm.m; The resistance between boreholes B1/B3 and B2/B4 are identical and cannot be distinguished graphically in the case of (e).

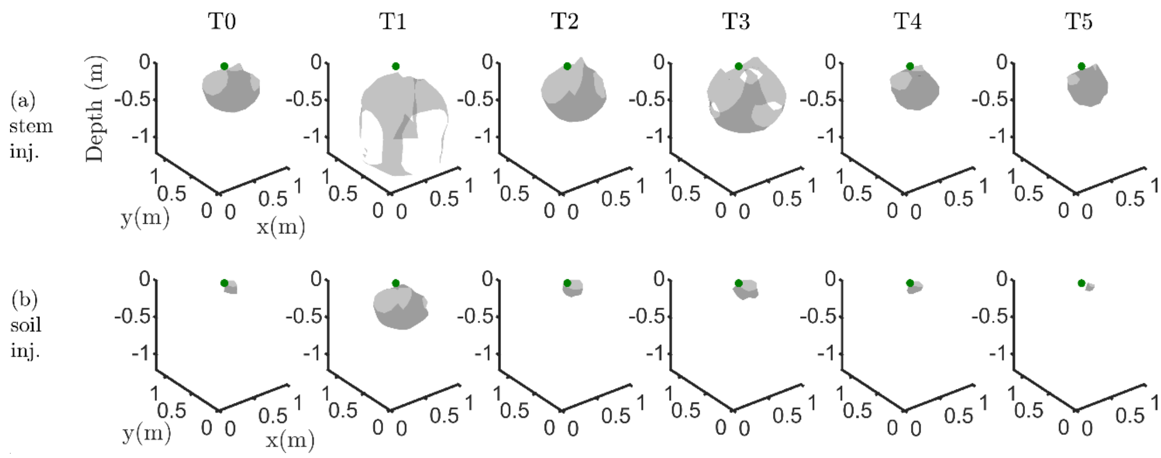


Figure 6: iso-surface minimizing the F_1 function for plant B; during stem injection (a), during soil injection (b); Columns represent the six times steps from T_0 to T_5. Green dot shows plant stem position. Threshold is defined by the misfit 25% of the normalised F_1 (value selected according to the evolution of the curve of sorted misfit F_1 and calculated for the tree injection at T_0 and kept constant for all the time steps).

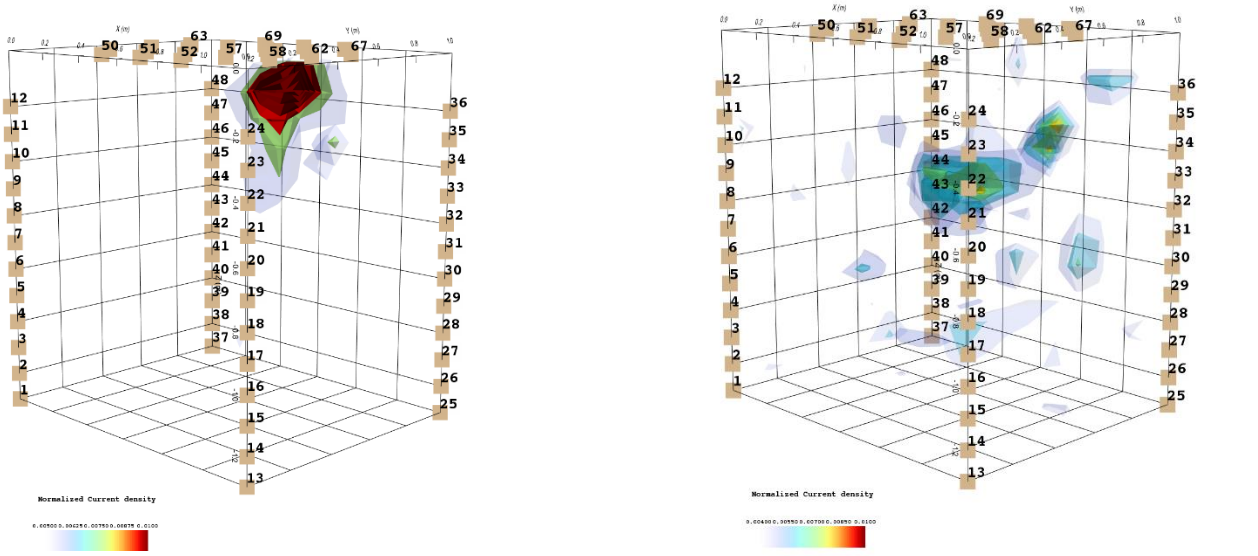


Figure 7: current source density after minimization of the objective function F_2 as defined in Eq. (4). The results are relevant to the background time T_0 for the plant B, for the soil current injection (left) and the stem current injection (right).

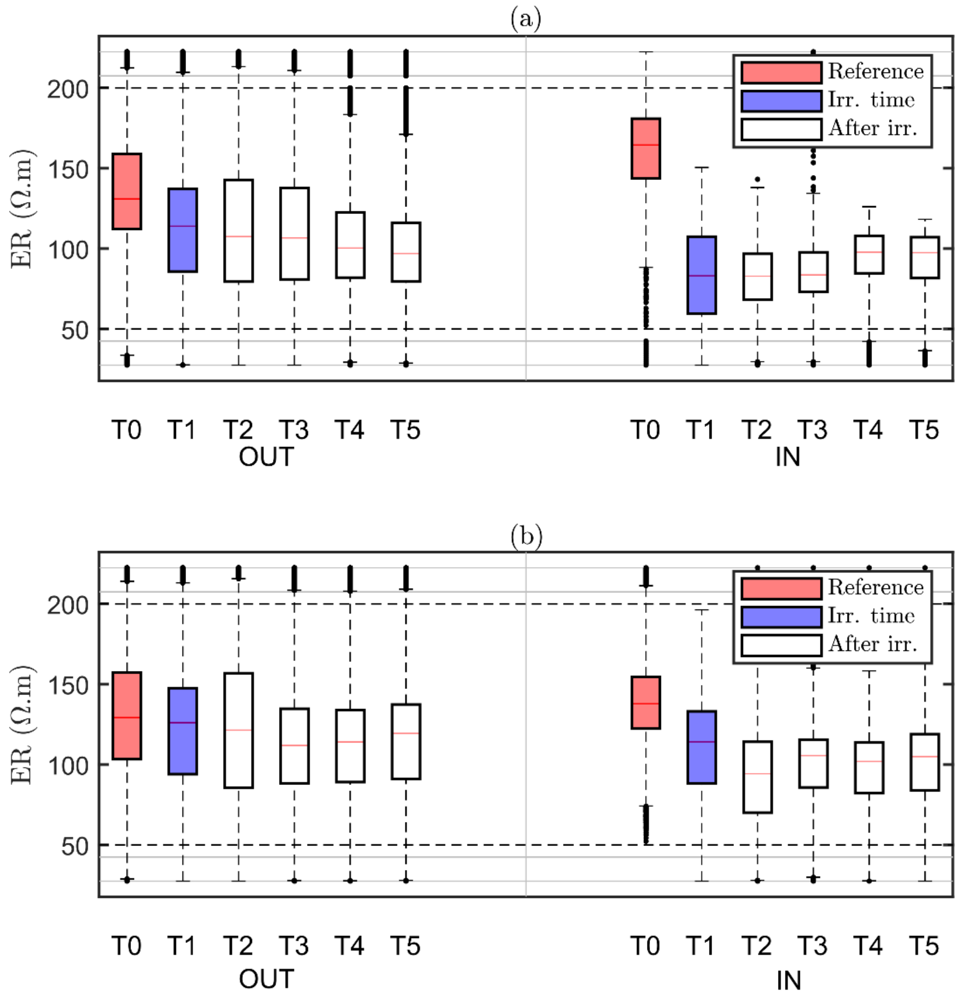


Figure 8: boxplot distribution of ER time variations observed on the plant A (top) and plant B (bottom), for the values selected outside (OUT, left part) and inside (IN, right part) of the region defined by the F_1 best fit sources (see Fig. 6a-T_0). The central mark indicates the median, the bottom and top edges of the box indicated the 25th and 75th percentiles of ER data, respectively. The whiskers extend to the most extreme data points not considered outliers. Each box corresponds to a given time step (see table 1), indicated in the x-axis.

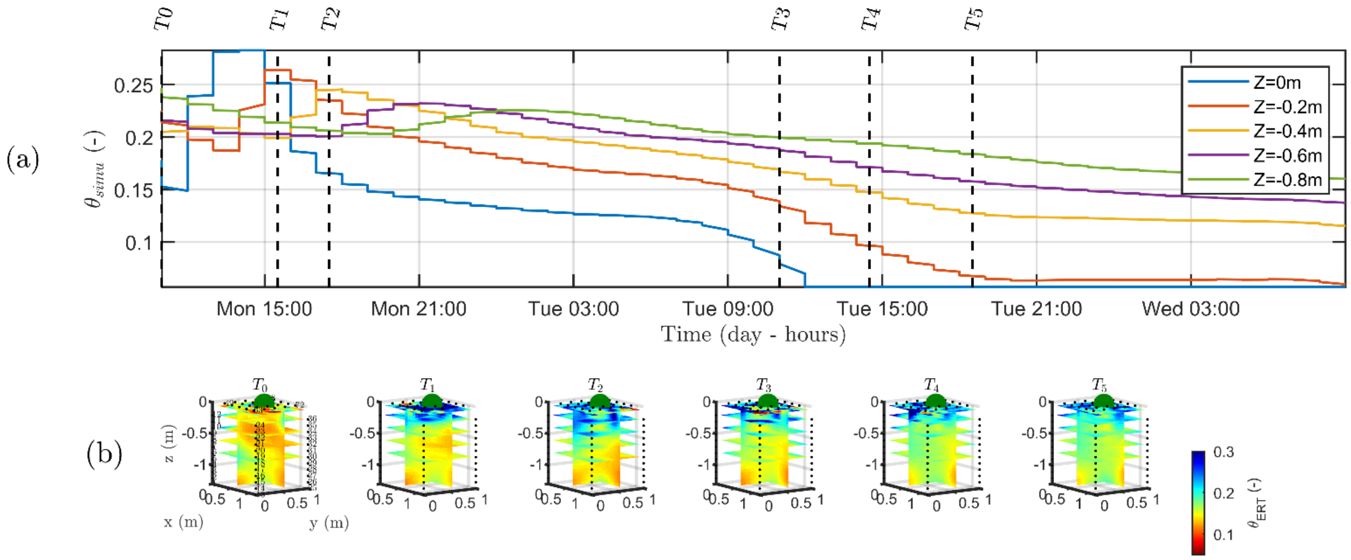
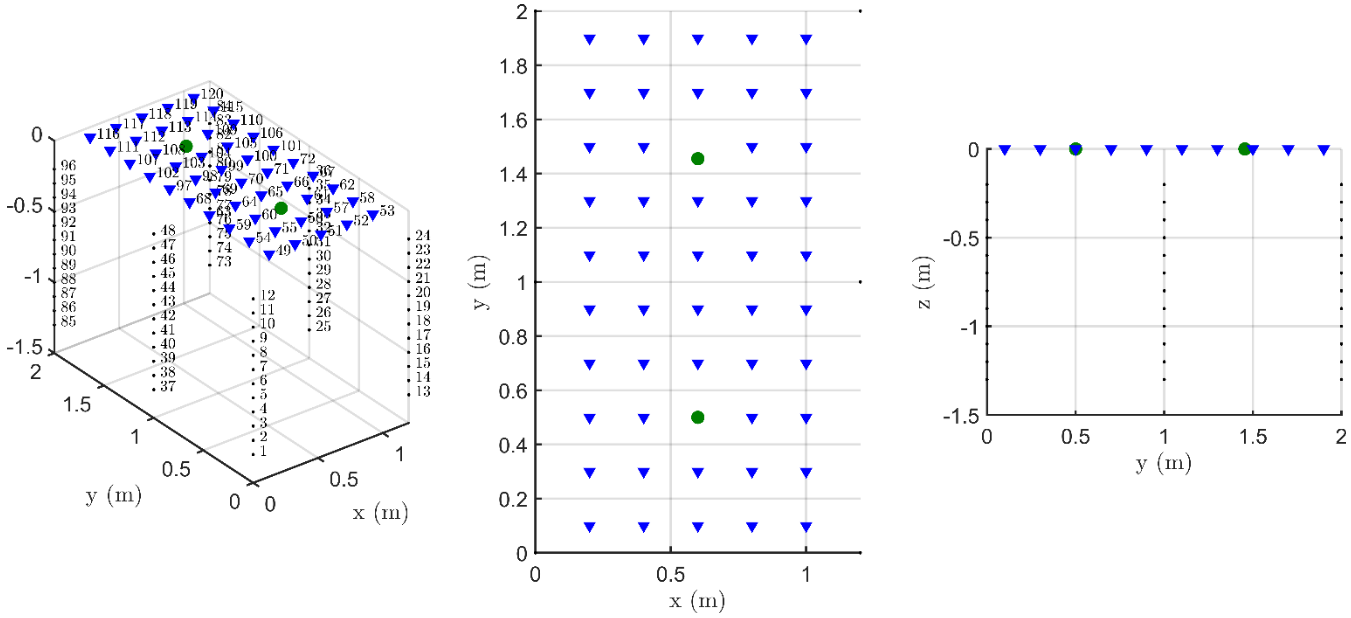


Figure 9: (a) time variation of simulated soil water content (θ_{simu}) at five depths. The vertical lines indicate the geophysical acquisition times (dashed and plain line respectively for the start and the end of the measurement, see Table 1). (b) 3D variations of the ERT-derived soil water content (θ_{ERT}) for the time steps describe in table 1. Horizontal layer depths are identical to the control points of the hydrological model.

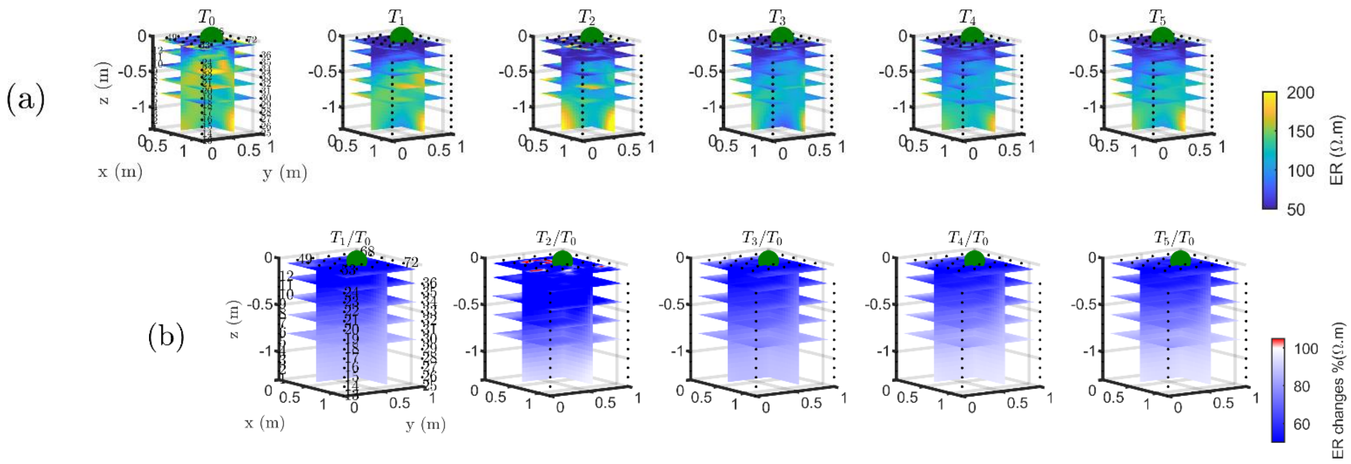
Appendix A: set-up description

Fig. A1: from left to right: 3D view of the surface (blue) and borehole (black) electrodes, view from the top and tranversal view. Plant A was located downhill. Green dot shows plant stem positions.



Appendix B: ERT monitoring

Fig. B1: 3D ERT results for plant A. The volume is sliced at the tree stem position (vertically) and at five depths (0.05, 0.2, 0,4, 0.6 and 0.8 m). (a) 3D inversion of the resistivity (in Ωm, log scale) from the background time T_0, during irrigation T_1 and after irrigation. (b) time-lapse inversion (following Cassiani et al., 2006) showing the ratios (in % of ER changes) between time step T_i and background time T_0 (100% in white means no change).



Appendix C: MALM monitoring

Fig. C1: Voltage distribution of the raw data of MALM time lapse monitoring for the plant B. First line results are relevant to the stem injection while second line refers to the soil control injection. Columns describe time evolution according to Table 1.

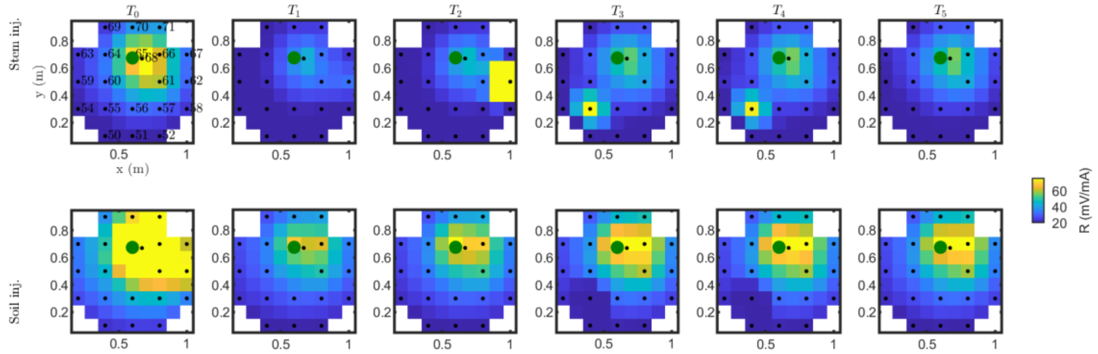


Fig. C2: Voltage distribution of the raw data of MALM time lapse monitoring for the plant A. First line results are relevant to the stem injection while second line refers to the soil control injection. Columns describe time evolution according to Table 1.

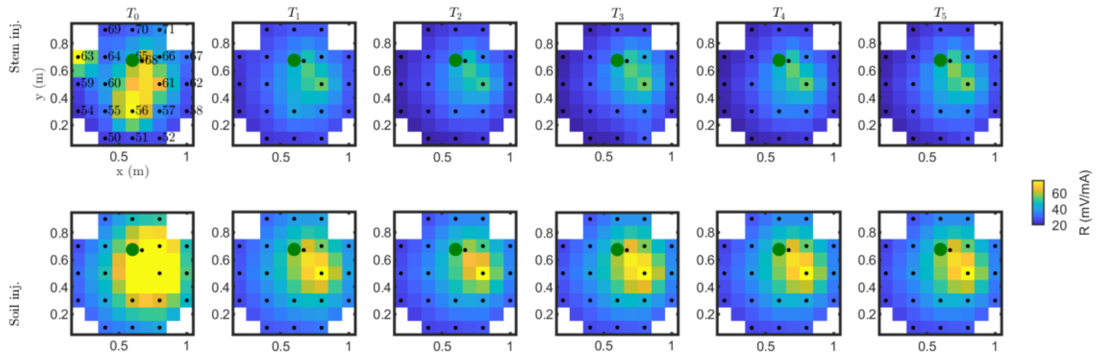


Fig. C3: iso-surface minimizing the F1 function for plant A; during stem injection (a), during soil injection (b); Columns represent the six times steps from T0 to T5. Green dot shows plant stem position. Threshold is defined by the misfit 25% of the normalised F1 (value selected according to the evolution of the curve of sorted misfit F1 and calculated for the tree injection at T0 and kept constant for all the time steps).

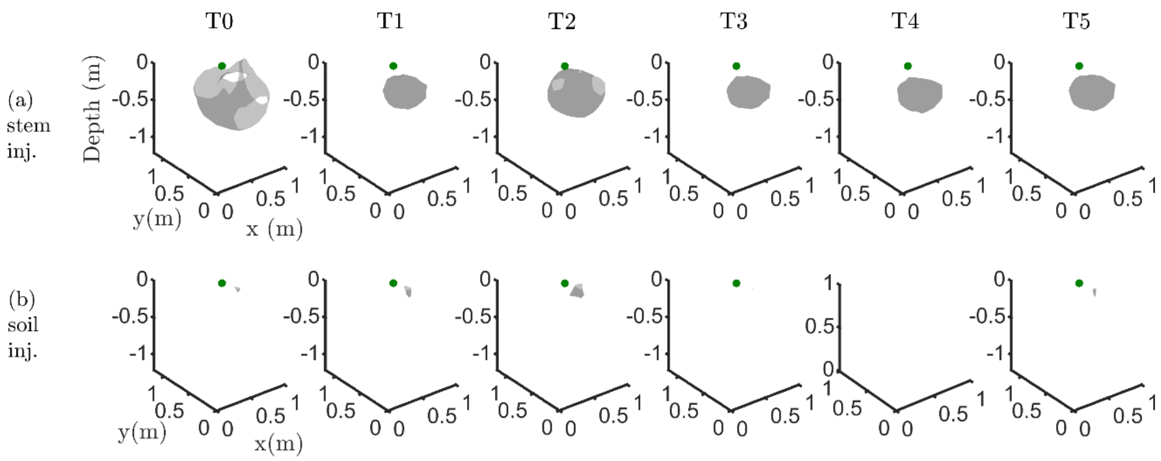
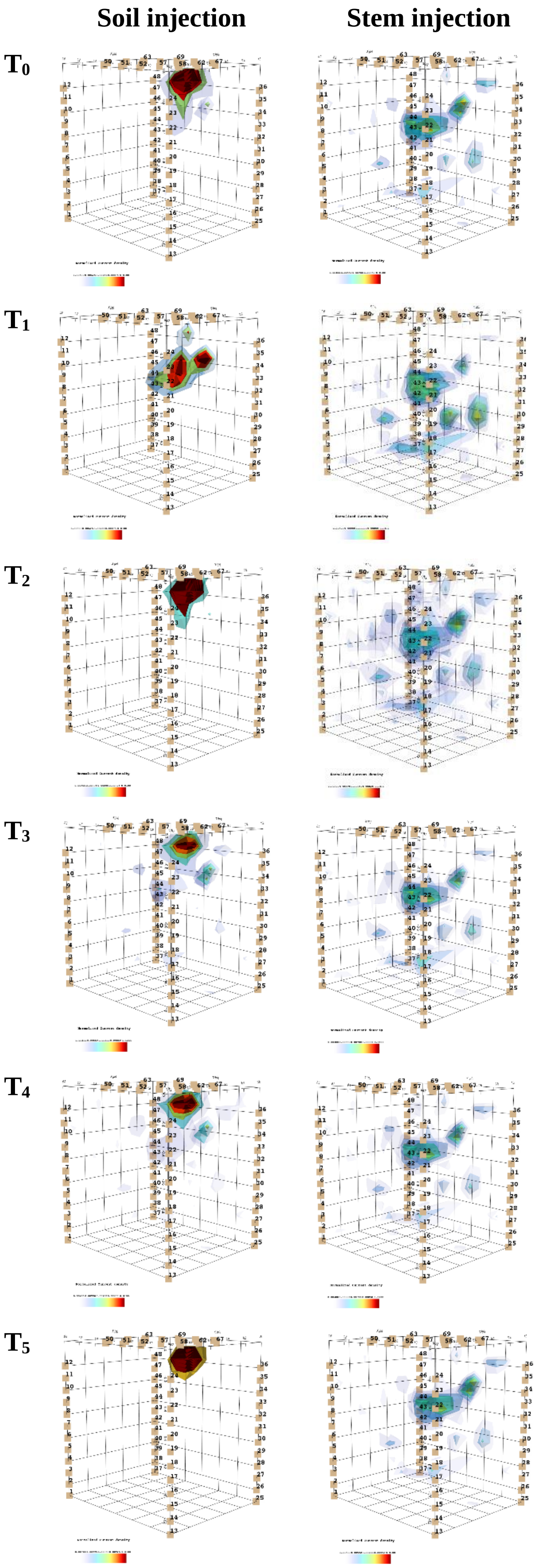


Fig. C4: Time-lapse evolution of the current source density after minimization of the objective function F2 as defined in Eq. (4). The results are relevant to the background time T0 to T5 for the plant B, for the stem current injection on the left, and soil current injection on the right.



SOIL Discuss., https://doi.org/10.5194/soil-2019-28-RC1, 2019

Interactive comment on "Time-lapse monitoring of root water uptake using electrical resistivity tomography and Mise-à-la-Masse: a vineyard infiltration experiment" *by* Benjamin Mary et al.

Anonymous Referee #1

Received and published: 7 June 2019

We thank the Reviewer for his/her comments. In the ensuing text, we try and address all raised issues. The reviewer's comments are reported in black, our replies in *italic blue*. Please also find attached a version of the manuscript with all changes highlighted in red.

B. Mary et al.

The manuscript "Time-lapse monitoring of root water uptake using electrical resistivity tomography and Mise-à-la-Masse: a vineyard infiltration experiment" by authors Mary et al investigates root characterization using the electrical MALM approach in a time lapse setting.

As explained in the manuscript, new approaches to non-, or minimally invasive root characterization are urgently needed to increase our knowledge about the root zone, as well as to provide better data input for soil-plant-atmosphere (SPAC) modeling frameworks. As such I think the topic of the manuscript is relevant to the readership of SOIL and well worth investigating. However, in its current state I cannot support a publication of the text under review without major revisions. Some parts of the manuscript feel somewhat rushed, and perhaps some (or most?) of my issues can be solved by reformulations or some additional text?

—————– General Comments: —————–

My two major concerns are:

1) No validation data: The study uses neither independent information on the rooting depth or distribution, nor are soil information such as soil water content measurements, Archie-Parameters, or soil temperature data used to support the statements made (or used in the analysis of the data). The fact of missing validation data is also mentioned in the abstract, although not further discussed in the text.

Validation of results on the basis of independent data is particularly challenging in the case of root water activity, and even worse in the case of field (not laboratory data). In order to deal with the lack of validation data, we took two actions:

1. *We added the results of a 1D hydrological infiltration model. The simulation results are compared against the spatio-temporal changes of SWC obtained from ERT after petrophysical transformation using Archie's law. A new section was added in the methodology part (nb 2.4).*
2. *We discussed the limits of validation data in our case. See discussion section.*

In light of the novel, very promising, technical approach of MALM I don't think this should prevent the publication of the text, yet it should be actively discussed and conclusions should be limited to statements that can be made without validation data. Perhaps the text could be reworked to provide/develop recommendations for future experiments that deal with the problem of obtaining suitable validation data? As such, the direct predecessor paper, Mary et al 2018, and this study could be positioned as discussing the technical details of the approach, preparing future studies which focus on the validation aspect.

Thanks for the suggestion. We feel this is indeed the message that should be conveyed by the paper. We added an explicit objective in this direction (see L. 123) and added a relevant paragraph in the discussion. Furthermore, all along the manuscript we moderated each of our interpretations acknowledging our lack of direct validation.

Overlap with Mary et al 2018: As far as I can see Mary et al 2018 and this study were conducted on the same field site and same plants within a few months time. As such they should be considered as companion studies. As far as I can see their stated objectives overlap massively (as do the conclusions):

Thanks for the suggestion to link the two papers using the companion paper option. We will deal with it for the re-submission.

2) Aims of Mary et al 2018 (page 5429): "1. define a viable field protocol that uses jointly MALM and ERT to map active tree vine roots, 2. propose and analyze algorithms capable of identifying the location of active roots, and 3. test the algorithms above against real data from a French vineyard."; Aims of this study: "(a) define a non-invasive investigation protocol capable of "imaging" the root activity as well as the distribution of active roots, at least in terms of their continuum description mentioned above; (b) Integrate the geophysical results with mass fluxes measurements in/out of the soil-plant continuum system." My reading is that all aims of Mary et al 2018 are contained in aim a) of this study.

We agree with the reviewer comment, aims were reformulated to better highlight the specificities of this paper (see L. 119-123)

"

This study had the following goals:

- *define a non-invasive investigation protocol capable of "imaging" the root activity as well as the distribution of active roots, at least in terms of their continuum description mentioned above, under varying soil water content conditions;*
- *integrate the geophysical results with mass fluxes measurements in/out of the soil-plant continuum system using a simple 1D simulation reproducing the infiltration experiment.*
- *give recommendations for future experiments focusing on the method validation.*

"

Adding to this, I was not able to find any information on the stated "integration of geophysical results with mass fluxes" (aim b) in the text, leaving only the duplicate aim a).

See previous answer.

Also note that the time-lapse aspect is currently not discussed in detail (detailed below) in the text, the analysis of the time-lapse data does not take into account any dynamics such as daily evaporation information, and the conclusion mostly reflects the conclusions of Mary et al 2018, without significant conclusions regarding the application of MALM within a time-lapse context.

This concern has been also raised by reviewer 3. In this respect we took the following actions:

- *Plot the full time-lapse data for ERT, MALM and current density for both plants and discussed it in detail (while this presentation/discussion was very limited in the first version of the manuscript). For those situations with no significant variations, plots are put into the appendix.*
- *The time-lapse variations are now discussed in light of the hydrological model. This allowed to clearly identify the dynamics such as daily evaporation and/or RWU.*

——————————————- Specific comments/technical corrections: ——————————————-

3) In addition, there are various (apparent?) inconsistencies between Mary et al 2018 and this text. However, this could be caused by the rather brief formulations in the text, not by actual errors. I suggest to rephrase.

We answered point by point hereafter.

3.1) Site description: Mary et al indicate sandy-clayey soil from 125-175cm, while this text puts this layer from 100-175m. I also wonder why the authors do not interpret the different information on root distribution given in Mary et al 2018. For example, Mary et al 2018 identifies the first soil layer as "with a first sandy horizon (0–40 cm depth), porous and soft." Looking at Figure 3 in this text, I wonder if the observed resistivity decrease in the upper 40 cm can be attributed to this porous layer, and correspondingly fast infiltration?

Simplifications in the text led to possible approximations but without any consequences on the data validity. At a depth larger than 100 cm the influence on our results is negligible, given the maximum depth of investigation of the electrode apparatus. We intended to describe the deepest layer only to highlight possible long-term water lift thanks to capillarity movements which could explain the shallow rooting depth hypothesized.

We rephrased the relevant sentences to make them consistent with the first article and we summarized the site description graphically in a new figure (as a support of the hydrological model)

The observed resistivity decrease in the upper 40 cm can be attributed to the porous layer, and correspondingly fast infiltration. We added a sentence to point it in the revised version of the manuscript L. 279

Note that in Mary et al 2018, the three layers were distinguished in term of root density and not in term of soil nature. Note that Figure 3 has been changed to highlight 3d feature as request by reviewer 3.

3.2) Mary et al 2018 state that active roots are located in the upper 0.3m (page 5436). This does not seem to be the case if the isosurfaces in Figure 6 (this text) are to be interpreted as root extension, although the same plants are measured. Note that this text also states, as one of the conclusions, that the MALM approach is relatively insensible to different water regimes, and thus I would expect similar results between both studies.

If this inconsistency is caused by slightly different interpretation of the term "active roots", I suggest to rephrase accordingly.

Obviously, the position of the active roots from one acquisition to the another (during different seasons) may vary. Sentence The sentence about 'active roots' has been rephrased to avoid misunderstanding.

First, in Mary et al. 2018, the value of 0.3 m has been validated using the target function F2, while the F1 plot is a spatial representation of the misfit (between measured data and individual source contribution). The misfit is normalized, but the threshold defined as the 25% percentile influencing the delineation of the "active" root zone is not directly comparable from one experiment to the other (see also answer for reviewer question nb 21).

Even though we think that function F1 might also be a good indicator for active roots, isosurfaces in Figure 6 of the manuscript mostly intend to show a straightforward comparison between soil and stem injection.

3.3) Mary et al 2018 introduces the "F2" inversion approach explicitly to improve upon the crude assumptions of the "F1" inversion (page 5432: "The F1 function can help guide the search for the region where the presence of active source is most likely to concentrate, but of course the use of F1 alone does not represent a realistic distribution of sources in the MALM inversion.")

I think the authors should thoroughly explain why the "F1" inversion is sufficient in this study, or even better, they should provide "F2" results. This would bring this text more in line with the other paper. Otherwise this could be interpreted as the authors downgrading their previous approach.

The reviewer is right, the F1 inversion is not sufficient per se to deduce root distribution but clearly convey the most interesting result of this article that is to say that the MALM results were corrected from variations of water content using ERT and thus are not sensitive to soil water content state which is the main problem for root detection using only ERT.

We took this comment into consideration and provide ALSO results from F2 inversion, and we took the opportunity to introduce some improvements as compared to the version used in the previous manuscript.

In the new version of the manuscript we adapted a robust algorithm to invert the data in 3D using the linearized form of the problem after Peruzzo et al. 2019 (Thesis.). The new features are (explained L. 246 to 260 of the revised version of the manuscript):

- *Regularisation using a L-curve analysis to control the regularisation weight.*
- *The code has been written for the 3D case and for an unstructured mesh.*

Most importantly all candidate sources are kept during the inversion of current density. Thus, there is no more a need to identify a threshold for which some sources are rejected. The misfit of F1 is transformed into a normalized initial model (m0) of current density via the inverse (1/F1) transformation. During the inversion of the current density, we adopted a relative smallness regularisation as a prior criterion for the inversion i.e. the algorithm minimizes $||m - m0||^2$, where m is the model parameter and m0 is a reference model to which we believe the physical property distribution should be close.

Result of F2 inversion are shown in the new version of the current manuscript.

—-

Line-specific comments:

4) line 39: what is the actual data that can be gained by the "new method"? In this regard, be more specific in lines 54/55: which data is required, which is extracted from MALM?

Sentence rephrased

In this study, we focus on new methods designed to image root systems and their macroscopic functioning, in order to help understand the complex mechanisms of these systems (the rhizosphere, e.g. York et al., 2016).

5) line 61: I think the "are" after "techniques" must be replaced by "is"

Ok done

6) line 106: "test" -> "tested"

Ok done

7) line 109: be more specific with regard to the field site and Mary et al 2018. I think it strengthens the study if the link to the previous paper is made more specific.

Ok done. Sentence added: "This paper is meant to be an extension of Mary et al. (2018) and to focus on an infiltration experiment"

8) line 114: as already stated, I'm missing this in the results/discussions

See response to comment 3.1 and 3.2 above.

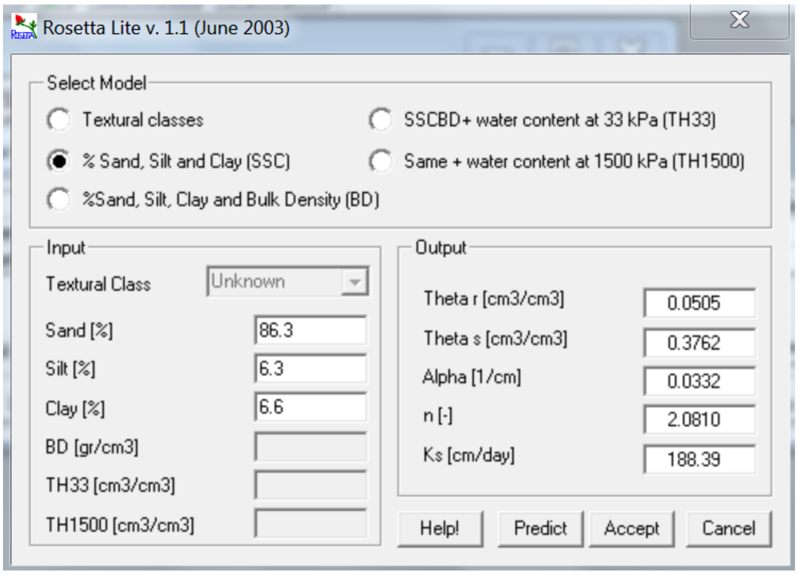
9) line 142: do you have any information on porosity/soil response to water content? Can you estimate an expected increase in resistivities due to the infiltration? Does the data fit any estimates?

These questions can now be answered thanks to the 1D hydrological modelling of the infiltration.

We here assumed that the retention and conductivity functions that describe the hydraulic properties of the soil can be represented by the Mualem-van Genuchten model (MVG, Mualem, 1976; van Genuchten, 1980.) Hydraulic properties of the soil were recovered directly from its grain size distribution – using Rosetta: see screen shot below.

Whilst this is a very simplified model, we were able to compare qualitatively the variations of resistivity with time with the infiltration simulation. To facilitate the comparison, electrical resistivities were transformed using Archie's law with the following parameters:

- *porosity, assumed to be equal to soil ϑs saturated water content;*
- *pore water electrical conductivity was assumed equal to the electrical conductivity of the water used for infiltration. The irrigation water had an electrical conductivity of 720µS/cm at 15°C. (0.072 S.m-1).*
- *m =1.3 (typical values notably described in Werban et al., 2008)*



10) line 165: can you be more specific on how you measure reciprocals for MALM? I would suspect totally different signal-to-noise environments, and correspondingly would deem the normal-reciprocal difference only as a weak proxy to data quality in this case, similar to nobody using normal-reciprocal differences for gradient or Schlumberger measurements.

Study of reciprocals were more thoroughly discussed in the first paper Mary et al. 2018. It has been shown that reciprocals were indeed not easy to correlate with data quality in MALM. This may be caused by non-linearities caused during current injection in the stem itself.

We rephrased the sentence to better state that reciprocals may not be the best solutions to estimate data quality in the MALM case.

11) section 2.4.1: can you provide error parameters used for the inversions? Is a target RMS of 1 reached for all time steps?

We added a sentence to explain this in the text (L. 212 and 215 to 218) and completed the table 1.

Table 1 shows the performance of the inverse model in absolute mode such as number of rejected measurements, and final root mean square (RMS) for an error level of 10 %. Most of the data converged after fewer than 5 iterations. Error level was assumed to be equal to the error used for the reciprocal analysis.

12) line 180: I suggest to rephrase and make clear that the voltage is measured with respect to the remote electrodes.

Sentence rephrased, see L225

13) equations 1 (and others): could you indicate vector/matrix entities? For example, in equation 2 it is not clear if the F1-value is the norm of all misfits for a given current injection, or only for the i-th value (I suspect it is the former, but in this case the notation must be corrected).

Equation 1:

Poisson equation was conserved in its general form without description of the vector/matrix entities.

Equation 2 and 3 were further described See L. 241 and 252 to 260

The reviewer is right, F1-value correspond only to the i-th value.

$F_1(D_m, D_{f,i}) = \|D_m - D_{f,i}\|_2$ *(2) changed to* $F_{1,i}(D_m, D_{f,i}) = \|D_m - D_{f,i}\|_2$

Equation 3:

$F_2 = \Phi_d + \lambda\Phi_m = W_\varepsilon \|d - f(m)\|_2^2 + \lambda(W_s \|m - m_0\|_2^2)$

14) line 186: I suggest to rephrase: the forward problem is unique, the inversion illposed. "relatively straightforward" is somewhat non-meaningful.

Sentence rephrased as (see L. 230 to 233):

"

Given a distribution of current sources, and once σ (x,y,z) is known from ERT inversion, the forward problem is uniquely defined and consists in the calculation of the resulting V field. Conversely, the identification of C(x,y,z) distribution given V(x,y,z) and σ (x,y,z) is an ill-posed problem, that requires regularization and/or a priori assumptions in order to deliver stable results.

"

section 2.4.2 (MALM) lacks quite some details to properly understand the approach and it took me a while to figure out that the details can be found in Mary at al 2018 (not only the discussion of different approaches). While you link to Mary et al 2018 in line 189, perhaps you could start the section with a sentence similar to: "The MALM analysis follows Mary et al 2018..." to indicate that this is just a short recap and the reader cannot expect a comprehensive explanation here.

The sentence has been changed according to suggestion (see L. 222)

Again, I wonder why you chose to only use the F1 approach. You state in lines 201ff: "While more advanced attempts could be made (such as the F2 approach also described by Mary et al., 2018) the simple F1 approach is capable of imaging the likely location of current sources in the ground, that in turn represent - according to our key assumptions – the locations where roots have an active contact with the soil." After reading through Mary et al 2018, I would expect a more detailed explanation, perhaps supported by numerical studies. Again, using only the F1 approach seems to contradict your findings in Mary et al 2018.

The reviewer's comment makes sense. We took two actions:

- *Plot the result of F2 inversion*
- *Rephrase the text to make it clear that F1 provides a feasible area of search to help F2 to converge (as explained in response to comments 3.2 and 3.3)*

15) line 193: I'm not sure if the term "likelihood" is suitable here, given that it usually is associated with stochastic/Bayesian problem descriptions. Why not call it a data misfit, or a current source RMS?

Ok changed accordingly: Likelihood has been replaced by misfit

16) section 3.1: Can you discuss more how you come to the conclusion that the intermediate depths are influenced by RWU (line 218-219)? Given the high irrigation rate of 115 l per hour (and ongoing infiltration), is the plant strong enough to take more water up than is infiltrated from above?

The question "is the plant strong enough to take more water up than is infiltrated from above?" finds a convincing answer (YES) in a previous work conducted also on Citrus trees (Cassiani et al.,2015) where this phenomenon is apparent.

Note that figure 3 has been changed to show ER absolute values and ER ratios for the full-time monitoring.

17) Are you sure that the high-conductive upper 40 cm in T1 are not cause by a somewhat higher porosity, compared to the layers below? (perhaps caused by the greater amount of roots reported in Mary et al 2018 for that layer?) Correspondingly, the anomalies in the "intermediate" region below could then be explained with a not-fully-saturated soil?

This is a speculation that is not supported by the data we have – although the presence of dense roots may increase soil porosity (at a larger scale than a typical soil sample, though).

18) Section 3.2/Fig 4: I'm wondering if showing measured resistances helps here, due to varying geometric factors. What about showing the ratio of measured voltage and the homogeneous solution (Fig. 4e)? Alternatively, just convert to apparent resistivities?

For a pole-pole acquisition and even more for a mise-a-la-masse acquisition, results as usually displayed using horizontal maps of normalized ***resistances – these are equivalent to voltages normalised on the injected current****. It has several advantages, in the perfect case, iso-potentials show directly the shape of the conductive body.*

19) line 250: "see Figure3Figure4" -> "see Figs. 3 and 4"?

Corrected.

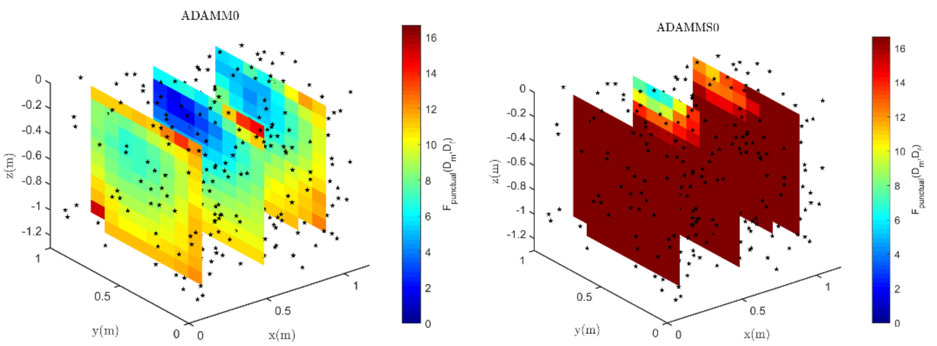
20) line 251: perhaps prepare an appendix with the corresponding results for plant B?

We have added an appendix for plant B

21) line 260: I'm wondering how the selection of the F1-threshold using the 25% percentile influences the delineation of the "active" root zone. In Mary et al 2018 their Figure 8 indicates possible threshold values of 35V (legend) or 17V (caption). Again, all for the same field site/plants. This seems inconsistent and should be discussed.

A value of the F1-threshold corresponding to the 25% percentile (here corresponding to 25% misfit) clearly influences the delineation of the "active" root zone as it can be appreciated from the misfit distribution below (time step T0 for the stem injection on the left, for the soil injection on the right).

See comment 23 for more details on the threshold determination.



22) In relation to 21, it would be nice if you could try to actually recover root information that could, theoretically, be used in the SPAC-modeling approaches, as motivated in the introduction. Can the MALM-approach provide information on root density, or only on root delineation? Can you extract an exemplary 2D rooting depth/rooting density map from your results?

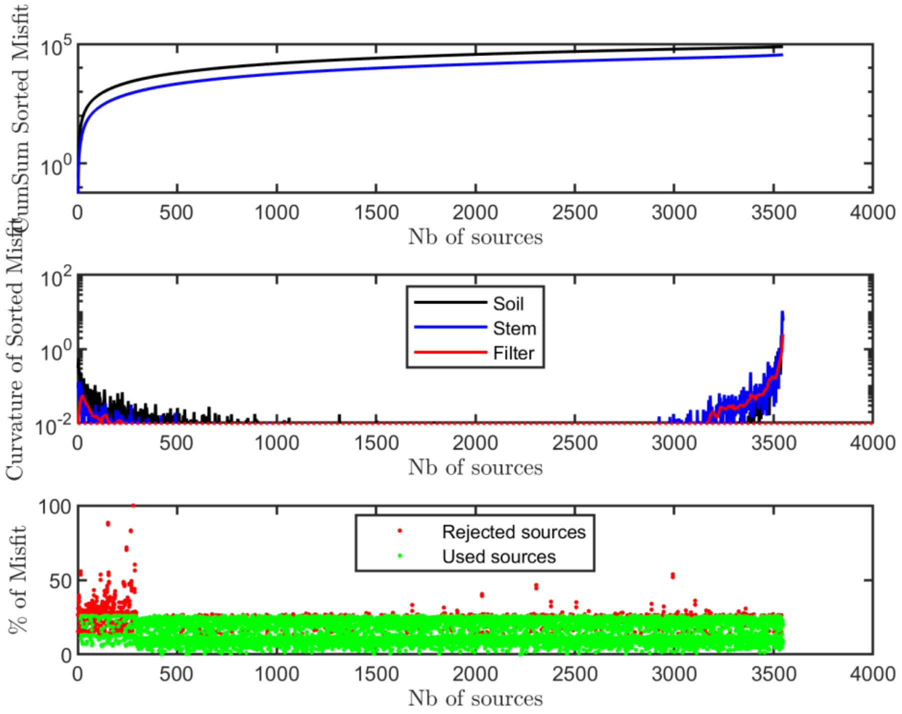
SPAC modelling approaches integrating root water uptake use empirical model describing the root system (Dupuy et al. 2010) and MALM could indeed provide relevant information in this respect. Our approach is adaptable to macroscopic RWU models that describe root water uptake as a sink, microscopic ones being too complex since they required knowledges in root hydraulic architecture. This has been more extensively considered and discussed in this revised version of the manuscript.

Using the average value of current density along horizontal planes we were able to plot the vertical profile which was tentatively used as rooting profile density for the 1D hydrological simulation.

We discussed the limitations of MALM and the uncertainties on delineating the root system considering that only the active root system may be highlighted. In some cases, the active root system is really local as compared to the entire root system extent and thus the picture we can retrieve from excavation. As far as enough data are available to describe time varying *active root location MALM can improve macroscopic RWU modelling. Recommendations to use destructive methods to complement MALM methods were also introduced.*

23) line 260: could you provide the curve of sorted F1-misfits in the appendix? This would ease the understanding of the F1-threshold.

We rephrased the sentence to make it clearer, but we did not overload the appendix with further figures. Below the curve of sorted misfit for T0 of plant B. See L. 320



24) line 268: I suggest to rephrase "absolute apparent"

Done

25) line 277: the F1-threshold of 7V is used to delineate root and soil zones?

Yes. We added a sentence to make it explicit. L. 345 to 348.

26) line 289: could you be more specific as to the resolution achieved here? My understanding is that the best resolution would be roughly the smallest electrode distance, which would be 10 cm here. Is this "high-resolution" in the context of root research?

Sentence rephrased

27) line 294: "...independent information... may help". Could you be more specific on how this additional information could be included into your workflow, apart from validating the results? Would it be possible for you to include any of this data in your inversion workflow, thereby minimizing uncertainties?

The first ERT-MALM coupling is already integrated in the workflow in the sense that we considered MALM as a non-soil water sensitive information to define the possible area of root. Separation of contributions of root zone and outer area on ER values extracted from ERT help distinguish between processes such as RWU and hydraulic redistribution (hydraulic lift in particular). This approach is more realistic compared to other approaches who used horizontally layered separation (Vanella et al.) to describe and separate the contributions.

The paragraph has been modified. See L. 384-393 of the new revised manuscript.

28) lines 296-302: I cannot follow your reasoning regarding the "second coupling" of ERT and MALM. By design MALM requires ERT results, and thus I'm having problems seeing this as a conclusion.

Sentence removed

29) line 303: I suggest to rephrase "successfully tested", as without validation we still do not know how reliable the results are.

Ok done

30) lines 310-310: "The soil injection leads practically to identifying the true single electrode location." I'm having trouble understanding the meaning of the sentence...could you elaborate or rephrase?

Sentence rephrased:

"

The soil injection leads practically to retrieve a current density close to a punctual injection (located at the true single electrode location)

"

31) line 310: I don't get the meaning of the first sentence, given that ERT and MALM solve completely different inversion problems, which guarantees that the results differ. Perhaps rephrase with regard to the emerging patterns of the results?

Here we described the situation where the stem electrode is replaced by one in the soil but close to the stem (we are not referring to ERT!).

The sentence was rephrased to make it clearer.

32) Conclusions: I fail to find much discussion of the time-lapse character of the present study, and much overlap with the aims/conclusions of Mary et al 2018. Perhaps you could focus the conclusions more on time-lapse-specific questions/answers? Does MALM provide more robust information in the light of varying water content regimes? Can MALM provide information on the actual RWU, perhaps by correlating to the estimated evaporation?

In the new version of the manuscript we try and correlate ER variations with estimated evapotranspiration and RWU. This also contributed to the second paper objectives which wasn't really fulfilled in the first version.

Questions "Does MALM provide more robust information in the light of varying water content regimes? Can MALM provide information on the actual RWU, perhaps by correlating to the estimated evaporation?" have been specifically addressed in the discussion section.

33) Will you provide all primary data and analysis results as a data repository, as required by SOIL?

Yes. We added a statement on "Data availability" section.

I sincerely hope these comments are not taken personally, but as constructive comments aimed a improving the message of the manuscript.

We are grateful to the reviewer, for its thorough reading of the manuscript and for all the very relevant comments.

Best regards

References:

Cassiani G., J. Boaga, D. Vanella, M. T. Perri, S. Consoli, 2015, Monitoring and modelling of soil-plant interactions: the joint use of ERT, sap flow and Eddy Covariance data to characterize the volume of an orange tree root zone, *Hydrol. Earth Syst. Sci.*, 19, 2213-2225, doi:10.5194/hess-19-2213-2015.

Mary, B., Peruzzo, L., Boaga, J., Schmutz, M., Wu, Y., Hubbard, S. S., and Cassiani, G.: Small-scale characterization of vine plant root water uptake via 3-D electrical resistivity tomography and mise-à-la-masse method, Hydrol. Earth Syst. Sci., 22, 5427-5444, https://doi.org/10.5194/hess-22-5427-2018, 2018.

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Interactive comment on "Time-lapse monitoring of root water uptake using electrical resistivity tomography and Mise-à-la-Masse: a vineyard infiltration experiment" *by* Benjamin Mary et al.

Anonymous Referee #2

Received and published: 11 June 2019

We thank the Reviewer for his/her comments. In the ensuing text, we try and address all raised issues. The reviewer's comments are reported in black, our replies in *italic blue*. Please also find attached a version of the manuscript with all changes highlighted in red.

B. Mary et al.

This manuscript deals with the application of geoelectrical methods for imaging and monitoring roots activity and water flow in the context of the soil-plant atmospheric continuum. The authors conducted time-lapse ERT and MLAM surveys around two grapevines plants differing in their age. The subsurface electrical resistivity was monitored before and after an infiltration experiment. The ERT data were inverted using a standard algorithm, and a simple algorithm for the imaging of the current source distribution was used. The work presented here is an extension of Mary et al (2018), but with the addition of an infiltration experiment, demonstrating the ability of the combined methods to monitor water content and RWU dynamics. Overall, the work presented is interesting for the reader of SOIL, the manuscript is well written, and the methods and data analysis are adequate.

The main pitfall is the lack of supplementary information that prevents a quantitative analysis of the (very interesting) dataset. Specifically, water content and water salinity were not measured or assessed. Differences between the transpiration of the two plants were not considered or measured (e.g., with sap flow meter). Nevertheless, even if this data is not available, the time lapse MALM provides qualitative information, at a high spatial resolution, on water content dynamics and RWU processes. In conclusion, I recommend publishing after some moderate revisions.

General comments:

1. The limitations in the interpretation of the results due to the lack of supplementary data (water content, salinity, formation factor) should be discussed in details.

We acknowledge the limited availability of supporting data. However, in order to strengthen the paper's conclusions we took two actions:

a) *We added a 1D hydrological modelling of the infiltration:*

Whilst this is a simplified model, we used a petrophysical transformations (Archie) on measured ER and thus recovered the spatial and time variations of soil water content.

b) *We discussed the limits of validation data in our case:*

We do agree that ancillary measurements are always welcome to support the geophysical information. Nevertheless, in this specific case they also have important limitations:

- *Validation through root excavation has numerous potential pitfalls. Among them, the destruction of fine roots during extraction that may prevent us from correlating root system architecture et geophysical observations. Discussed L417 to 423*
- *SWC can only be measured at few specific spatial locations. Discussed L. 425*

2. In my view, one of the most interesting parts is the maps in Figure 5, showing the time-lapses differences between the young and old plants. However, a discussion on this observation is missing. Figure 5 is not mentioned in the text at all (perhaps in L252). I would strongly suggest to give a detail explanation of those results and to link them to the expected behavior of the different plants.

The reviewer might have misunderstood the meaning of the Fig. 5. Maps in Figure 5 showed differences between the MALM stem injection and its companion soil injection (as explained in the section MALM acquisition 2.3). Also, reviewer 3 reported that the figure was redundant with Fig. 4 and was not sufficiently mentioned. We then decided to remove it and improve Fig. 4 instead to better convey the idea i.e. raw map of MALM potential contains time lapse information and show significant differences between stem and soil injection.

As for the comparison between plants A and B, this has not been neglected since in the initial version of the manuscript we discussed the differences between the two plants (see L. 265/266, 275/276, 314, 319, …).

Specific comments:

1. L123: I guess that the water holding capacity is related to the pore size distribution and not to the porosity.

Correct. We rephrased the sentence accordingly.

New sentence: "

Due to its larger particles and thus high porosity and smaller surface area, the sandy layer has a relatively poor water retention capacity.

" See L. 132 of the revised manuscript

2. L142: you report the EC of the irrigation water, but what is the EC of the pore water? Do you expect heterogeneity in the pore water salinity? This should be discussed.

For the hydrological model reproducing the infiltration test, pore water conductivity was assumed equal to electrical conductivity of the water used for infiltration.

We have good reason to think that this assumption can hold in our case since the infiltration was relatively intensive (> 100L/h) and the initial soil pores were then filled with irrigation water. We nevertheless agree with the reviewer comment that EC of the pore water is not necessarily equal to the EC of the irrigation. We did not consider specific rhizosphere processes such as root exudation, which could affect the water content estimates. We assumed, no salt accumulation taking place near the roots, i.e. passive solute uptake only with no active uptake, exclusion or exudation. Solute movement models exist to consider the different root processes that might affect the constant concentration in water pores. Significant solute gradients may arise around roots due to processes mentioned above. If they were to occur, the water content estimates could be impacted by such gradients. However, in this specific case the volume of irrigated water and the short residence time is likely to make these processes second order effects.

3. L223: Due to the lack of supplementary information, the arguments about the size and extent of the root systems are not solid enough. Is it the size of the root system or the total transpiration that differ?

If the reviewer is talking about the differences between the shape of the two plants, we do agree that a pure comparison of their root system is not realistic from our result. Nevertheless, this is clearly not the point of this study.

Nevertheless, the reviewer raised an interesting question that we tried to address in the discussion (see section 4.1 of the revised manuscript)

Interactive comment on SOIL Discuss., https://doi.org/10.5194/soil-2019-28, 2019.

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Interactive comment on "Time-lapse monitoring of root water uptake using electrical resistivity tomography and Mise-à-la-Masse: a vineyard infiltration experiment" *by* Benjamin Mary et al.

Anonymous Referee #3

Received and published: 14 June 2019

We thank the Reviewer for his/her comments. In the ensuing text, we try and address all raised issues. The reviewer's comments are reported in black, our replies in *italic blue*. Please also find attached a version of the manuscript with all changes highlighted in red.

B. Mary et al.

Review comments on Mary et al., 2019 SOIL This paper by Mary et al., proposed a novel and integrated geophysical monitoring framework to investigate the complex soil root system, especially focusing on assessing the root water uptake and delineating the active root density. Such multidisciplinary and innovative research should be encouraged and supported as the authors are developing tools to provide quantifiable and potentially spatiotemporal intensive data for SPAC modeling. However, there are few major flaws in this paper that prevent it from publishing in its current form. I suggest the authors redesign the experiment, revise and expand the current manuscript according to the reviewers' comments, and resubmit it. Some general comments:

1. I assume this paper is meant to be an extension of Mary et al (2018) and to focus on infiltration experiment. However, the datasets presented in this study and the affiliated discussions are not sufficient for a regular full paper, particularly, the lack of linking to any ground-truth data (such as soil samples, soil water chemistry, TDR measurements, rhizotron measurements, and so on). The authors also did not the full advantage of their >24 hours time-lapse measurements, only limited snapshots are presented without quantitative analysis. As a result, it is not convincing that this work has advanced the work from Mary et al., (2018), yet exhibits problematic overlaps.

Indeed, this can be viewed as a companion paper of the previous paper by Mary et al. (2018) – the same was suggested by Rev.1; note that the results contained in both papers are different, complementary to each other, and too extensive to be summarised in a single paper, referring also to different experiments. Given this, we reformulated the objectives of this paper to better convey its originality and importance as compared to the paper by Mary et al. (2018):

The objectives are:

- *define a non-invasive investigation protocol capable of "imaging" the root activity as well as the distribution of active roots, at least in terms of their continuum description mentioned above;*
- *integrate the geophysical results with mass fluxes measurements in/out of the soil-plant continuum system using a simple 1D simulation reproducing the infiltration experiment.*
- *give recommendations for future experiments that deal which focus on the validation aspect.*

Furthermore, in the revised version of the manuscript we took care of showing the full advantage of the time-lapse measurements by:

- *showing the time-lapse variation of absolute ER inverted values for all time steps*
- *inverting and showing the time-lapse ratios after time lapse inversion of ERT data*
- *showing the time-lapse variation of MALM for all time steps*

Also, in the revised version and in order to comply with the new objectives, we present the results of a 1D simulation of the infiltration experiment. The time-lapse results are now discussed in the light of the hydrological model. This allowed to clearly identify the dynamics such as daily evaporation and/or RWU.

Finally, in the revised version of the manuscript (also considering the comments by Reviewer 1) we also improved the inversion algorithm in the F2 formulation.

2. In both current study and Mary et al., (2018), the biggest technical issue is that the electrode spacing is too small (0.1 m) and this might have violated the point-source assumption. The authors didn't explain what the electrodes they were using, or how deep the electrodes were buried in the ground. But from Figure 1 in this paper, it seems like authors used standard stainless steel electrodes with at least 10 cm into the ground (equal or even greater than the electrode spacing) This is extremely important as the current course in such setup (electrodes too close to the target and experiment dimension is on the same order as of the target) is very likely not 'point-source' anymore, and the noise could overwhelm the actual data due to target property changes. Such electrode mislocation errors can be very complicated but can be simulated in synthetic experiments. Furthermore, due to the principle of reciprocity, such data error cannot be caught and eliminated by reciprocal measurements. There are few studies on this problem and I strongly suggest the authors read related literature. I personally had failed experiments before due to this very reason.

The reviewer is right at raising the question but is wrong in his/her conclusions that we used standard electrodes buried as deep as 10 cm. <u>We are perfectly aware of the issues</u> related to the assumption of point sources inherent in most inversion algorithm, and <u>we have 20 year experience in small scale ERT applications</u> where these issues are constantly taken into account – the literature is well known. In this particular case the risk is invariably that of having an apparent conductive layer at the surface. And the impact in time-lapse measurements tends to be factored out, of course.

Nevertheless, not that the surface electrodes are 1.4 mm in diameter, but are stuck in the ground by no more than 3 cm – note that the soil surface is very irregular between the rows of the vineyard due to field work of the land surface.

3. The results and discussion are too brief and qualitative to provide an in-depth discussion on how the ERT and MALM reveal the actual root functions. For the readership of this journal, the actual root-soil mechanisms that were revealed and supported by geophysical methods are very appealing. The authors did a time-lapse (>24 hours) experiment, why the time-lapse ERT resistivity changes or MALM results are not shown? Only the initial condition and 2-hr snapshot are shown? More time-step data would provide significantly more information into the root system function.

Thanks for the suggestion. In the revised version of the manuscript, the time-lapse ERT resistivity changes, derived from a time-lapse ratio inversion and MALM results for all time steps and for both plants are presented (plant B shown only in appendix for brevity). Also, a dedicated section was added to discuss integration of ERT with the hydrological model and ET data.

4. More detailed soil information and geophysical survey design information should be provided.

Soil information (type, roots density and granulometry) is now reported in the new figure 2a and a detailed scheme of the survey design is now added in appendix A1.

5. An illustration showing the borehole locations is very necessary. Also, please label the borehole number in the geophysical results plots as well.

See previous comment. All the electrodes numbering is now labelled in the figures.

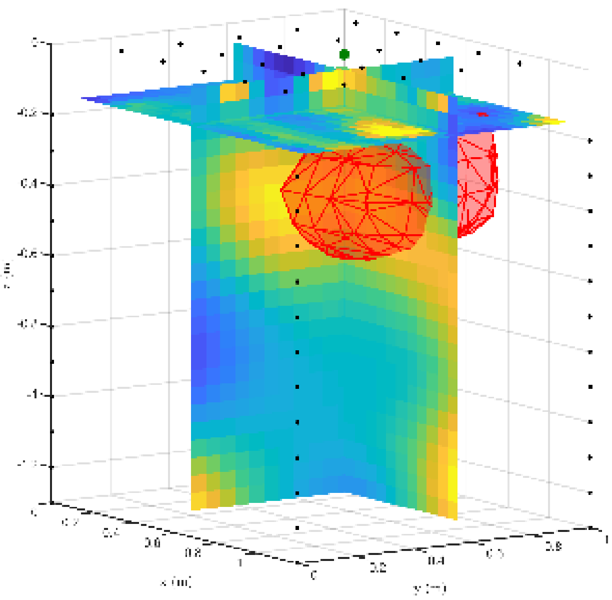
6. Figure 5 shows the normalized voltage ratios for plant B, but this figure was not discussed or mentioned in the manuscript.

Figure 5 has been removed from the new version of the manuscript because the raw MALM data does not provide a straightforward information. We added in the appendix the time-lapse variation of the absolute normalised voltage measured.

7. Figure 7 and the corresponding text section 3.4 are difficult to follow. First, where is the boundary of this estimated active root zone? What are the exact times from T1 – T5? Are these boxes representing all the ER values outside and inside the zone? Or just selected values?

- *Our assumption is that the region identified by MALM F1 (albeit very rough) for the background time corresponds to the RWU region. The inner area (IN) is then defined as the area within the closed isosurface at the background time T0.*
- *The times for T1 to T5 are given in the table 1 (note that there is no exact time since the measurement last approximately 30min. Legend has been rephrased to stressed out this (We invite the reader to report to this table otherwise the figure would be overloaded).*
- *Boxes represent selected values inside and outside the hypothetic rooted zone. Left size figure boxes refer to the OUT zone while right size to the IN. Figure and figure legend were improved to better convey this.*

For the reviewer information we show hereafter a plot the boundary of the active zone below to illustrate our comment.



8. Line 150. It is not very clear what is the electrode spacing for the surface electrodes, 0.1 m? what is the exact measurement configuration? The current description is too brief to get the idea of how the measurements were done (for example, any surface to borehole electrode pairs for current injection?) I've tried to read the Mary et al. 2018 paper, despite the similarity between these two studies, the ERT/MALM acquisition was not fully explained in that paper either.

In the revised version of the manuscript we detailed the set-up geometry adding a figure in appendix A1.

We also added a more in-depth description of the protocol (see L. 165).
"
The total dataset includes three types of measurements: 430 surface-to-surface, 2654 surface-to-borehole and 4026 in-hole measurements.
"

9. Figure 3 needs to be improved with better visualization showing the 3D feature. The facets are not distinct in this current plotting style and the authors may organize the subplots into two rows for easier comparison.

The new figure shows now the 3D pattern via a combination of vertical and horizontal slices through the 3D interpolated ER, slice positions were chosen to correspond to the control point of the hydrological simulation.

Detailed comments:

Line 35. Is the word 'expended' supposed to be 'expanded'? *Corrected*
Line 36. SPAC is repeated. *Deleted*
Line 37. I suggest more references here besides the work by Dirmeyer et al.,

Added a reference to Newman et al., (2006).
"Newman, B. D., Wilcox, B. P., Archer, S. R., Breshears, D. D., Dahm, C. N., Duffy, C. J., McDowell, N. G., Phillips, F. M., Scanlon, B. R. and Vivoni, E. R.: Ecohydrology of water-limited environments: A scientific vision: OPINION, Water Resour. Res., 42(6), doi:10.1029/2005WR004141, 2006."

Line 39. More references should be included.

We added a sentence and a reference to Richter and Mobley, (2009).
"Richter, D. deB. and Mobley, M. L.: Monitoring Earth's Critical Zone, Science, 326(5956), 1067–1068, doi:10.1126/science.1179117, 2009."

Line 55. Can the authors reiterate the main motivation of the work?

Sentence rephrased:
"

However, calibration requires that suitable data such as roots and soil water content evolution are available in a form comparable with the model to be calibrated.

"

Line 85-94. This part introduces the potential of SP and IP in monitoring water update and root systems. However, this part seems to be a bit out of place as the prior and following paragraphs discuss the actual methods have been used in this study. Suggest moving this part to either prior to ERT or after MALM.

Thanks. Done

Line 209. 'less intense', what does this mean?

“Intense” replaced by “resistive”

Line 213 – 214. ‘The input of low resistivity water (15 Ohm.m, measured in laboratory) caused a homogeneous drop of the resistivity values that make the two images around plant A and plant B very similar to each other’. How much is the resistivity decrease? Could you give a specific number? Maybe the authors can plot the delta resistivity (difference) for both plant A and B and show more time-step results.

Thanks for the suggestions.
In the revised version of the manuscript we added the time-lapse inversion to evaluate the resistivity decrease or increase in term of % of change on the ratios between two consecutive times for both plants.
Absolute change of ER is about 50 Ohm.m and up to 100 Ohm.m (added in the revised manuscript L. 278)

Figure 6. Please label ‘stem/soil injection’ directly on the plot to aid the reading.

Done

Interactive comment on SOIL Discuss., https://doi.org/10.5194/soil-2019-28, 2019.