

**Manuscript soil-2019-28 – Minor revision**

**B. Mary et al.**

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

Dear Editor, dear reviewers,

We thank again the reviewers for their careful reading.

In the revised version of the manuscript text, we addressed all raised minor changes. Please also find attached a version of the manuscript with all changes highlighted.

Data are now available on the open data repository of the University of Padova.

Based on these changes, we would be grateful if you would consider the revised manuscript for publication in Soil.

Best regards,

*B. Mary et al.*

## **Report 1**

Review of the revised version of: "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.

The main revisions in the revised version of the manuscript are: (1) addition of a 1D hydrological model of the infiltration; (2) an extended discussion on the limited availability of supporting information; (3) reformulation of the objectives; (4) extended discussion on time-lapse data. Overall, I think that the authors did a good job addressing the reviewers' comments and improved the manuscript significantly. Attached are some comments, which after their consideration, I believe the manuscript can be accepted for publication.

1. L160 – please also give the electrode length

*Sentence rephrased "a better contact in the loose soil and were heavier and more firmly grounded (3cm out of 12)"*

2. L187 – It is not clear enough how you process the results from the MALM to obtain a 1D root length density. Please explain how that was achieved.

*The reader should refer to L. 197 for more details. Sentence rephrased.*

3. Table 1 – Instead of the number of data points used for the inversion, can you please give the percentage of data that passed the reciprocity error threshold?

*Ok done*

4. L217-218 – Can you provide information about the % of data that did not pass the 2% error?

*Ok done. Sentence rephrased.*

*At this threshold 65% (in mean) of the data passed the reciprocity. A total number of 687 points were used during the inversion after selection of common set between all-time steps.*

5. L261 and Fig 3. – In the text you refer to the wrong Fig. please correct. In Fig. 3 you have wrong references to the a and b panels.

*Ok done*

6. Make sure to correct all the references to Fig. 3 (e.g., L261, L263, 264)

*Ok done*

7. L275 – correct the ref. to the figure.

*Ok done*

8. In Fig. 5, the graphs for the boreholes. It is not clear what each of the lines means, i.e., which fig. is related to a specific borehole.

*Ok we added a legend to identify the boreholes numbering*

9. Rephrase L340-341

*Done*

10. L 356 – missing Ref to Figure

*Refs added*

11. Section 3.5 – Plotting 1D profiles of the resistivity (say under the root zone) can help in the comparison between the observed and modeled dynamics.

*Since we modelled and show only the variations of soil water content we limited the plots to the 1d profiles of converted resistivity to SWC.*

12. L401 – missing "in" ( "results \_\_\_\_ a simple")

*Ok thanks*

## **Report 2**

Dear authors, dear editor,

the manuscript "Time-lapse monitoring of root water uptake using electrical resistivity tomography and Mise-à-la-Masse: a vineyard infiltration experiment" describes electrical tomographic measurements on two vine plats during an infiltration experiment. Here, the MALM method is further investigated as a means to infer the distribution of active root distributions, based on the basic premise that electrical current, injected into the stem of plants, follows the root elements down to their endings, thereby forming a relationship between root (end) distribution and electrical measurement characteristics.

This is the first revision of the manuscript -- I also reviewed the initial submission.

In general, I think the authors substantially improved the manuscript and shaped the discussion of the available data. I also think that the MALM method, coupled to imaging, will see substantial activity in the upcoming years, which will make this manuscript part of a substantial base of knowledge from which to investigate further.

Yet, I think some (minor) aspect still could use some polishing, and in general I found a small number of inconsistencies/mistakes. Therefore, I suggest a minor revision to provide enough time for polishing the presentation and go over the text again.

Comments:

- line 96/97: in this regard the study of Rao et al, 2019 would be a nice addition to the references, dealing with exactly this type of influence.

<https://doi.org/10.2136/vzj2019.04.0037>

*Done*

- line 145/146: I'm not a soil scientist, but based on the soil description (sand), the generally low precipitation in the month preceding the experiment, and the high air temperature, I would expect the SWC to be below field capacity, and more approaching the wilting point (my reasoning: the reported 18 mm cumulative precipitation in the month before would be gone after 4 days at 5 mm/day, and even ignoring runoff and drainage, at this point SWC would fall below field capacity).

*We agree with the reviewer comment and replaced close by below*

- line 160: electrodeS -> electrode

*Done*

- line 161: I'm not sure I understand the notation of "(3/cm)"

*Corrected (3cm out of 10)*

- line 168: support -> supported

*Done*

- line 171: "remoteS" -> "remote"

*Done*

- line 187: result -> resultS

*Done*

- What are the Archie-Parameter used? What is the assumed porosity distribution? I understand that you provide some of the answers in the review-reply, but would strongly suggest to include them also in section 2.4.

*We added the missing Archie-Parameters used and the assume porosity distribution*

*The porosity was assumed to be equal to the soil saturated water content ( $\vartheta_s$ ), the cementation factor ( $m$ ) equal to 1.3 and the saturation exponent ( $n$ ) equal to 1 (typical values notably described in Werban et al., 2008).*

- eq (1), comma after equation

*Done*

- eq (2): I would suggest to differentiate vectors by printing them bold (as done in line 228 for C).

Similarly, it would be nice to also mark matrices differently (eq. 3). My suggestion would be to write vectors and matrices in bold, with lower characters assigned to vectors, and upper characters to matrices.

*Done for eq. 2 and 3*

- eq 3: I believe that  $W_{\text{eps}}$  and  $W_s$  need to be moved into the norms (this would be consistent with standard least-squares inversion theory). Also, currently you try to apply a Matrix ( $W_{\text{eps}}/W_s$ ) to a single value (the norms). End equation 3 with a point (end of sentence)

*Done*

- is there any normalization included for the  $F_2$  inversion? I.e., does the injected current always sum up to 1 Ampere (or any other normalization constant?).

*Yes, we applied the current conservation law to normalise  $F_2$ . Sentence added "Lastly, current conservation was respected since the sum of  $c_j$  was equal to 1 at the end of the inversion iterations."*

- section 2.5.2 in general: Reading just this section, I get the strong sense that the  $F_2$  inversion is the one that should actually be analyzed, and  $F_1$  is only used to determine a suitable reference/starting model (lines 254++). Yet, later on the  $F_1$ -result are still prominently analysed (3.3/3.4), while the  $F_2$  inversion results are only shortly discussed lines 336-341. I suggest to adjust the formulations accordingly.

*We think that function  $F_1$  might also be a good indicator for active roots and that a straightforward comparison between soil and stem injection can be achieved with it. With our methodology,  $F_1$  provides a feasible area of search to help  $F_2$  to converge and the extension of  $F_1$  was very similar to  $F_2$ . Yet this assumption is not supported by numerical studies but we would like to investigate it to offer a simple way to process MALM data without having to go through an inversion. This line of research has been initiated with the contributions of Binley et al (Late 90's)\**

- Rephrase the text to make it clear that line 264: citation error in pdf

*Corrected*

- Fig 3: increase size of colorbar

*Done*

- line 261: figure references should be figs 3 and 4, I believe

*Corrected*

- lines 267 - 272: These three sentences are inconsistent. The first one discuss a low resistive layer (consistent with ERT figures), but the second and third one actually argue for increased resistivities using RWU. :-)

*The explication for the increased resistivities using RWU related to resistive anomalies at intermediate depths. Sentence relocated for more consistencies.*

- lines 203 vs 275: the conductivity of irrigation water is inconsistent between both lines. Line 203 mentions a conductivity of 720 mu S/cm, which I believe convert to 13.88 Ohm m, while line 275 gives 15 Ohm m.

*Corrected*

- line 280: Figure reference misses the figure number (should be fig 4?)

*Yes done*

- Fig 4b: To be honest, I find the values confusing. Why not show percentage changes with respect to T0? But I suppose this is a matter of personal taste, so please ignore.
- eq 4 (and sentence after): comma after equation. Also, I would suggest to add a note that this is only valid for pole-pole measurements, to prevent any confusions.

*We rephrase the previous sentence to make clear that this is the voltage distribution due to a single current electrode*

- Graphics quality in general should be checked (could be a matter of the review pdf)

*All figures are now at least produced with 300dpi.*

- lines 286-294: I suggest to only talk in terms of resistances - it is can be quite confusing to first read eq 4, and then only see resistances in Fig 5 (this is a presentation thing, you correctly mention the normalization).

*Done for this paragraph*

- caption of Fig 5/line 625: here equation 2 is mentioned, yet you show raw data and I believe 5e depicts computations with eq. 4?

*True thanks. Corrected*

- Fig 5: relate colors of vertical plots to electrode boreholes (e.g., to electrode numbers in Fig. 7)

*Done*

- line 346: missing Figure reference number

*Done ref added*

- Fig. 8: what are the dots? Data points determined as outliers?

*Yes, added in the legend for clarity.*

- line 367: showS -> show

*Done*

- line 429: perhaps replace "next" by "near"?

*Done*

- section 4.2 reads very pessimistic, and implies that traditional methods are not reliable and cannot be used for validation of MALM. I would argue that traditional root sampling methods, although labour intensive and with known limitations regarding fine root detection, should be the first line of validation, given that soil/root sciences have been working with this data for decades. Only in the second line of argumentation should alternative means be discussed. Also, in the case of vine plant roots, which I believe are of the woody nature, even a destructive sampling by trench method should provide a pretty good idea of root distribution. Coupled with knowledge about water distribution by traditional ERT, the intersection of both distributions should provide us with a pretty good first estimate of where RWU can be expected (and such help to validate MALM results).

*Ok sentence moderated accordingly*

- - In general, I propose to rework the figures for:

- consistent styling/layout
- proper figure sizes (I believe that final figures should be either 8.3 cm (single column) or 12 cm in width, and it seems to me that a lot of figures will have really small/unreadable text after adjusting for these sizes.
- fix overlapping labels (e.g., fig 5).

*Done*

- line 694, caption of Fig C4: descriptions of left and right panel are swapped

*Corrected*

Looking forward to seeing the published version

*Thanks!*

Best regards

# 1 Time-lapse monitoring of root water uptake using electrical resistivity 2 tomography and Mise-à-la-Masse: a vineyard infiltration experiment

3 Benjamin Mary<sup>1</sup>, Luca Peruzzo<sup>2,3</sup>, Jacopo Boaga<sup>1</sup>, Nicola Cenni<sup>1</sup>, Myriam Schmutz<sup>3</sup>, Yuxin Wu<sup>2</sup>, Susan  
4 S. Hubbard<sup>2</sup>, Giorgio Cassiani<sup>1</sup>

5 <sup>1</sup>Dipartimento di Geoscienze, Università degli Studi di Padova, Via G. Gradenigo, 6–35131 Padova, Italy

6 <sup>2</sup>Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA, 94720,  
7 USA.

8 <sup>3</sup>EA G&E 4592, Bordeaux INP, University Bordeaux Montaigne, 1 allée Daguin, 33607 Pessac, France

9 Correspondence to: Benjamin Mary ([benjamin.mary@unipd.it](mailto:benjamin.mary@unipd.it))

10 **Abstract.** This paper presents a time-lapse application of electrical methods (Electrical Resistivity Tomography – ERT – and  
11 Mise-à-la-Masse – MALM) for monitoring plant roots and their activity (root water uptake) during a controlled infiltration  
12 experiment. The use of non-invasive geophysical monitoring is of increasing interest as these techniques provide time-lapse  
13 imaging of processes that otherwise can only be measured at few specific spatial locations. The experiment here described was  
14 conducted in a vineyard in Bordeaux (France) and was focused on the behaviour of two neighbouring grapevines. The joint  
15 application of ERT and MALM has several advantages. While ERT in time-lapse mode is sensitive to changes in soil electrical  
16 resistivity and thus to the factors controlling it (mainly soil water content, in this context), MALM uses DC current injected in  
17 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  
18 the same where root water uptake (RWU) takes place. Thus, ERT and MALM provide complementary information about the  
19 root structure and activity. The experiment shows that the region of likely electrical current sources produced by MALM does  
20 not change significantly during the infiltration time in spite of the strong changes of electrical resistivity caused by changes in  
21 soil water content. Ultimately, the interpretation of the current source distribution strengthened the hypothesis of using current  
22 as a proxy for root detection. This fact, together with the evidence that current injection in the soil and in the stem produce  
23 totally different voltage patterns, corroborates the idea that this application of MALM highlights the active root density in the  
24 soil. When considering the electrical resistivity changes (as measured by ERT) inside the stationary volume of active roots  
25 delineated by MALM, the overall tendency is towards a resistivity increase during irrigation time, which can be linked to a  
26 decrease in soil water content caused by root water uptake. On the contrary, when considering the soil volume outside the  
27 MALM-derived root water uptake region, the electrical resistivity tends to decrease as an effect of soil water content increase  
28 caused by the infiltration. The use of a simplified infiltration model confirms at least qualitatively this behaviour. The  
29 monitoring results are particularly promising, and the method can be applied to a variety of scales including the laboratory  
30 scale where direct evidence of roots structure and root water uptake can help corroborate the approach. Once fully validated,  
31 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  
32 conditions.

33

## 34 **1 Introduction**

35 The interaction between soil and biota is one of the main mechanisms controlling the exchange of mass and energy between  
36 the Earth's terrestrial ecosystems and the atmosphere. Philip (1966) was the first to use the phrase “soil–plant–atmosphere  
37 continuum” (SPAC) to conceptualize this interface in the framework of continuum physics. Even though more than five  
38 decades have elapsed and many efforts have been expanded (e.g., Maxwell et al., 2007; de Arellano et al., 2012; Anderegg et  
39 al., 2013; Band et al., 2014), the current mechanistic understanding or modelling of SPAC is still unsatisfactory (e.g. Dirmeyer  
40 et al., 2006, 2014 and Newman et al., 2006). This is not totally surprising, since soil–plant interactions are complex, exhibiting  
41 scale- and species-dependence with high soil heterogeneity and plant growth plasticity. In this study, we focus on new methods

42 designed to image root systems and their macroscopic functioning, in order to help understand the complex mechanisms of  
43 these systems (the rhizosphere, e.g. York et al., 2016). This diversity of interactions presents an enormous scientific challenge  
44 to understanding the linkages and chain of impacts (Richter and Mobley, 2009).

45 Roots contribute substantially to carbon sequestration. Roots are the connection between the soil, where water and nutrients  
46 reside, to the other organs and tissues of the plant, where these resources are used. Hence roots provide a link in the pathway  
47 for fluxes of soil water and other substances through the plant canopy to the atmosphere (e.g. Dawson and Stiegwolf, 2007).  
48 These transpiration fluxes are responsible for the largest fraction of water leaving the soil in vegetated systems (Chahine,  
49 1992). Root Water uptake (RWU) influences the water dynamics in the rhizosphere (Couvreur et al., 2012) and the partitioning  
50 of net radiation into latent and sensible heat fluxes thereby impacting atmospheric boundary layer dynamics (Maxwell et al.,  
51 2007; de Arellano et al., 2012). Yet, a number of issues remain when representing RWU in both hydrological and atmospheric  
52 models. Dupuy et al. (2010) summarize the development of root growth models from its origins in the 1970s with simple  
53 spatial models (Hackett and Rose, 1972; Gerwitz and Page, 1974) to the development of very complex plant architectural  
54 models (Jourdan and Rey, 1997). Dupuy et al. (2010) advocate for a different approach, where root systems are described as  
55 “density” distributions. Attempts in this direction (Dupuy et al., 2005; Draye et al., 2010; Dupuy and Vignes, 2012) require  
56 much less specific knowledge of the detailed mechanisms of meristem evolution, and yet are sufficient to describe the root  
57 “functions” in the framework of continuum physics, i.e. the one endorsed by the SPAC concept. These models also lend  
58 themselves more naturally to calibration against field evidence, as they focus on the “functioning” of roots, especially in terms  
59 of RWU (e.g. Volpe et al., 2013, Manoli et al., 2014). However, calibration requires that suitable data such as root density and  
60 soil water content evolution are available in a form comparable with the model to be calibrated. This is the main motivation  
61 behind the work presented herein.

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

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

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

82 In the investigation of roots and RWU the most widely used non-invasive technique is Electrical Resistivity Tomography (ERT  
83 – e.g. Binley and Kemna, 2005). ERT measures soil electrical resistivity and, in time-lapse mode, resistivity changes over  
84 time. Electrical resistivity values depend on soil type and its porosity, but also on state variables such as the saturation of

85 electrolyte (water) in the pores, and the concentration of solutes in the pore water (as described e.g. by the classical Archie's  
86 law, 1942). Note, however, that other factors may play a role, such as clay content (Rhoades et al., 1976; Waxman and Smits,  
87 1968) and temperature (e.g., Campbell et al., 1949). However, in general, it is possible to estimate water content changes from  
88 changes in electrical resistivity over time (and space) provided that pore water salinity does not vary dramatically. While ERT  
89 has been attempted for quantifying root biomass on herbaceous plants (e.g. Amato et al., 2009), the main use of this technique  
90 in this context aims at identifying changes in soil water content in space and evolution in time (e.g., Michot et al., 2003, 2016;  
91 Srayeddin and Doussan, 2009; Garré et al., 2011; Cassiani et al., 2012, Brillante et al. 2015). With specific reference to RWU,  
92 Cassiani et al. (2015, 2016), Consoli et al. (2017) and Vanella et al. (2018) used time-lapse ERT with 3D cross-hole  
93 configurations to monitor changes in soil electrical resistivity caused by irrigation and RWU for different crops (apple and  
94 citrus trees). It should also be noted that RWU and the release of different exudates by fine roots modify soil water content and  
95 resistivity at several temporal scales (York et al., 2016).

96 On the other hand, evidence suggests that roots themselves may produce signals in ERT surveys (Amato et al., 2008; Werban  
97 et al., 2008); however, these signals are often difficult to separate from soil heterogeneities and soil water content variations  
98 in space ([Rao et al., 2019](#)). Nevertheless, in most cases, the ranges of electrical resistivity of soil and roots overlap, and while  
99 the amplitude of contrasts varies according to the soil resistivity and tree species (e.g. Mary et al., 2016), the direct  
100 identification of root systems using ERT is often impractical.

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

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

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

124

125 **2 Methodology**

126 **2.1 Site description**

127 The study was conducted in a commercial vineyard (Chateau La Louviere, Bordeaux) in the Pessac Leognan Appellation of  
128 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  
129 °C and about 800 mm annual precipitation. Grapevine trees are planted at 1 m distance along the rows, and the rows are spaced  
130 about 1.5 m. We focused our interest on two neighbouring plants.

131 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  
132 depth. Due to its larger particles and thus smaller surface area, the sandy layer has a relatively poor water retention capacity.  
133 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  
134 about the plants and soil type). We concentrated our monitoring on only two neighbouring grapevines (Fig. 1), which differ in  
135 age and size: plant A was smaller and younger, plant B was considerably larger and older.

136 **2.2 Meteorological measurements and irrigation schedule**

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

147 The controlled infiltration experiment was conducted using a sprinkler installed between the two monitored plants, placed at  
148 an elevation of 1.4m, in order to apply irrigation water as uniformly as possible. The irrigation started on June 19, 2017 at  
149 13h00 and ended two hours later (15h00) for a total of 260 litres (104 l/h). Runoff was observed due to topography and probably  
150 induced more water supply for plant A that is located downhill. The irrigation water had an electrical conductivity of 720µS/cm  
151 at 15°C.

152 **2.3 ERT and MALM data acquisition**

153 We carried out a time-lapse ERT acquisition, based on custom-made ERT boreholes (six of them, each with 12 electrodes),  
154 plus surface electrodes (Fig. A1). The six boreholes were placed to form two equal rectangles at the ground surface. Each  
155 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  
156 each rectangle. The boreholes were installed in June 2015 and a good electrical contact with soil was already achieved at the  
157 time of installation. The topmost electrode in each hole was 0.1 m below ground, with vertical electrode spacing along each  
158 borehole equal to 0.1 m. In each rectangle, 24 surface stainless steel electrodes (14mm diameter), spaced 20 cm in both  
159 horizontal directions, surrounded the plant stem arranged in a five by five regular mesh (with one skipped electrode near the  
160 stem). Note that after testing smaller electrodes size in surface, we finally adopted larger ones since they ensured a better  
161 contact in the loose soil and were heavier and more firmly grounded (34cm ~~out of 12~~) to resist irrigation. We conducted the  
162 acquisitions on each rectangle independently. Each acquisition was therefore performed using 72 electrodes (24 surface and  
163 48 electrodes in 4 boreholes) using an IRIS Syscal Pro resistivity meter. For all measurements we used a skip 2 dipole-dipole

164 acquisition (i.e., a configuration where the current dipoles and potential dipoles are three times larger than the minimal  
165 electrode spacing). The total dataset includes three types of measurements: 430 surface-to-surface, 2654 surface-to-borehole  
166 and 4026 in-hole measurements.

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

174 Each MALM acquisition was accompanied by a companion MALM acquisition where the current electrode C1 was placed  
175 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  
176 current can be evidenced directly comparing the resulting voltage patterns resulting from the two MALM configurations.

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

181 We adopted a time-lapse approach, conducting repeated ERT and MALM acquisitions over time in order to assess the evolution  
182 of the system's dynamics under changing moisture conditions associated with the infiltration experiment. We conducted  
183 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  
184 acquisitions and the irrigation times is reported in Table 1.

#### 185 2.4 Forward hydrological model and comparison with geophysical results

186 Hydrus 1D (Simunek, J. et al., 1998) was used to simulate cumulative infiltration and water content distributions for plant B  
187 (the larger one). The results~~s~~ from geophysical data acquisition were used to feed the hydrological model initial conditions.  
188 Boundary conditions were set for the column respectively as an atmospheric BC with surface run off (observed during the  
189 experiment) and triggered irrigation for the upper part, and free drainage for the lower part (see Figure 2). We assumed that  
190 the retention and hydraulic conductivity functions can be represented by the Mualem-van Genuchten model (MVG, Mualem,  
191 1976; van Genuchten, 1980). Soil hydraulic parameters were directly inferred using grain size distribution and the pedo-  
192 transfer functions from the Rosetta software (Schaap et al., 2001). From the pit information (Mary et al., 2018), we assumed a  
193 uniform soil type along a 1D column ranging from 0 to 1.2m depth (Figure 2c). We used two types of time variable boundary  
194 conditions: (i) the irrigation rate changing with time, which was measured during the course of the experiment, and (ii) the  
195 potential evapotranspiration estimated according to meteorological data. We neglected direct evaporation. The root profile has  
196 been inferred from the MALM result at background (pre-irrigation) time using the average value along horizontal planes  
197 (Figure 2b) discretised every 20cm. We used the functional form of RWU proposed by Feddes et al. (1978) with no water  
198 stress compensation and a non-uniform root profile between 0 and 0.7 m depth.

199 The link between the forward hydrological and the geophysical model is a petrophysical relation which transforms electrical  
200 resistivity distributions into the corresponding simulated water content ( $\theta_{ERT}$ ) distributions. There are several petrophysical  
201 models of varying complexity to relate water content with electrical resistivity (e.g. Archie, 1942; Waxman and Smits, 1968;  
202 Rhoades et al., 1976; Mualem and Friedman, 1991). We adopted Archie's approach with the following parameters; pore water  
203 conductivity was assumed equal to the electrical conductivity of the water used for the irrigation (720  $\mu$ S/cm) for all the time  
204 steps. The porosity was assumed to be equal to the soil saturated water content ( $\theta_s$ ), the cementation factor (m) equal to 1.3

205 and the saturation exponent ( $n$ ) equal to 1 (typical values notably described in Werban et al., 2008). We considered  
 206 homogenous soil distribution, so only one petrophysical relationship was necessary. Initial water content was inferred after  
 207 transformation and reduction by averaging to 1D the ER values obtained during background time  $T_0$ . We obtained a non-  
 208 homogeneous initial water content for the hydrological simulation varying from 0.1 to 0.27 cm<sup>3</sup>.cm<sup>-3</sup> (Fig. 2a). In order to  
 209 compare the model results with the geophysical data, we used control points at 0, 0.2, 0.4, 0.6, 0.8m depth.

210 **2.5 Data analysis and processing**

211 **2.5.1 Micro-ERT time lapse analysis**

212 The inversion of ERT data was conducted using the classical Occam's approach (Binley and Kemna, 2005). We conducted  
 213 both absolute inversions and time-lapse resistivity inversions, as done in other papers (e.g. Cassiani et al., 2015, 2016). We  
 214 used for inversion only the data that pass the 10% reciprocal error criterion at all measurement times. A large percentage of  
 215 the data had reciprocity errors below this threshold. We inverted the data using the R3t code (Binley, 2019) adopting a 3-D  
 216 mesh with very fine discretization between the boreholes, while larger elements were used for the outer zone. Most of the  
 217 inversions converged after fewer than 5 iterations, and the final RMS errors respect the set convergence criteria (Table 1). For  
 218 the time lapse inversion, we followed the procedure described e.g. in Cassiani et al. (2006) in order to get rid of systematic  
 219 errors and highlight changes in term of percentage of ER ratios compare to the background time. Time-lapse inversions were  
 220 run at a lower error level (consistently with the literature – e.g. Cassiani et al., 2006) equal to 52% (consistently with the  
 221 literature – e.g. Cassiani et al., 2006). At this threshold 65% (in mean) of the data passed the reciprocity. A total number of  
 222 687 points were used during the inversion after selection of common set between all-time steps.

223 **2.5.2 MALM modelling and source inversion**

224 The MALM processing applied to a plant is thoroughly described in Mary et al (2018). Here we only recall the mathematical  
 225 background on which the method relies on and some advances compare to the previous approach described by Mary et al.  
 226 (2018).

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

$$229 \quad \nabla \cdot (\sigma \nabla V) = C \quad \text{---} \quad (1)$$

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

$$242 \quad F_{1,i}(\mathbf{d}_m, \mathbf{d}_{f,i}) = \|\mathbf{d}_m - \mathbf{d}_{f,i}\|_2^2 \quad , \quad (2)$$

243 where  $\mathbf{d}_m$  is a vector of measured voltage (normalised), and  $\mathbf{d}_{f,i}$  is a vector of modelled voltage corresponding to a single  
 244 source injecting the entire known injected current at the  $i$ -th node in the mesh. The forward modelling producing the  $\mathbf{d}_{f,i}$

245 values is based on the direct solution of the DC current flow in a heterogeneous medium, such as implement in the R3t Finite  
 246 Element code (Binley, 2019). Thus, the  $F_1$  inversion accounts naturally for the heterogeneous electrical resistivity of the 3D  
 247 soil volume, also in its evolution over time (e.g. as an effect of irrigation and RWU).  
 248 A more advanced objective function, which considers the presence of distributed sources, has also been introduced by Mary  
 249 et al. (2018). Here we propose several important changes to that approach, on the basis of the work by Peruzzo et al. 2019 who  
 250 proposed a linearized form of the problem. In this case, the cost function  $F_2$  consists of error-weighted data misfit  $\Phi_d$  and  
 251 model roughness  $\Phi_m$  containing model relative smallness and smoothness both weighted by the regularization parameter  $\lambda$ :

$$252 \quad F_2 = \Phi_d + \lambda \Phi_m = \mathbf{W}_e \|\mathbf{d} - \mathbf{f}(\mathbf{m})\|_2^2 + \lambda (\mathbf{W}_s \|\mathbf{m} - \mathbf{m}_0\|_2^2) \quad (3)$$

$$253 \quad F_2 = \Phi_d(\mathbf{m}) + \lambda \Phi_m(\mathbf{m}) = \|\mathbf{W}_e(\mathbf{d}_m - \mathbf{f}(\mathbf{m}))\|_2^2 + \lambda (\|\mathbf{W}_s(\mathbf{m} - \mathbf{m}_0)\|_2^2) . \quad (3)$$

254

255 Given a set of  $N$  voltage measurements, minimization of the objective function,  $F_2$ , given by [Eq. \(3\)](#), produces a vector of  $M$   
 256 current sources densities  $\mathbf{c}_j$  ( $j = 1, 2, \dots, M$ ), where  $\mathbf{d}_m$  is the data vector,  $\mathbf{f}(\mathbf{m})$  is the forward model that relates the model  
 257  $\mathbf{m}$  to the resistances,  $\mathbf{W}_s$  is a smoothness operator,  $\mathbf{W}_e$  is an error weighting matrix, and  $\lambda$  is a regularization parameter that  
 258 determines the amount of smoothing imposed on  $m$  during the inversion. An L-curve analysis is used to identify the optimal  
 259 regularisation parameter  $\lambda$ . In the revised algorithm all candidate current sources are kept during the inversion. Thus, there is  
 260 no more a need to identify a threshold for which some sources are rejected. However, the misfit of  $F_1$  is transformed into a  
 261 normalized initial model ( $\mathbf{m}_0$ ) of current density via the inverse ( $1/F_1$ ) transformation. During the inversion of the current  
 262 density, we adopted a relative smallness regularisation as a prior criterion for the inversion i.e. the algorithm minimizes  $\|\mathbf{m} -$   
 263  $\mathbf{m}_0\|^2$ , where  $\mathbf{m}_0$  is a reference model to which we believe the physical property distribution should be close. [Lastly, current](#)  
 264 [conservation was respected since the sum of  \$\mathbf{c}\_j\$  was equal to 1 at the end of the inversion iterations.](#)

## 265 3 Results

### 266 3.1 Background, irrigation time and monitoring of ERT measured data

267 The soil electrical conductivity during the period prior to irrigation (see ERT results in [Figure 2b](#)-Figure 2a and [3a3b](#),  
 268 respectively for plants A and B) ranged from 50 to 200  $\Omega\text{m}$ , with a median value around 100  $\Omega\text{m}$ , a range that is reasonable  
 269 for a dry sandy soil. For plant A, the smaller plant, the highest resistivity values were distributed at about 0.5 m depth ([Figure](#)  
 270 [2b](#)[Figure 2a](#)). For the larger plant B (Figure 2), the positive resistivity anomalies are more diffused and less resistive (150  $\Omega\text{m}$ )  
 271 compared to plant A, which reach larger depths. The very small-scale anomalies observed at the soil surface are likely to be  
 272 caused by heterogeneous direct evaporation patterns or different soil compaction. [The background time \( \$T\_0\$ \) for both plants](#)  
 273 [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.](#) More interesting  
 274 are the resistive anomalies at intermediate depths. [The background time \( \$T\_0\$ \) for both plants revealed a low resistive layer](#)  
 275 [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  
 276 et al., 2015, 2016, Consoli et al., 2017; Vanella et al. 2018), these higher resistivity values are likely to be linked to soil  
 277 saturation decrease caused by RWU, particularly in consideration of its intensity during this time of the year (June) for non-  
 278 irrigated crops. Of course, we cannot fully exclude that higher resistivity is also related to woody roots presence, especially  
 279 when they are dense. Besides, roots could also have induced soil swelling creating voids acting like resistive heterogeneities.  
 280 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  
 281 irrigation, so the variations of ER values are not directly comparable for the two plants. [Error! Reference source not found.](#)  
 282 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  
 283 resistivity water ([13.8845](#)  $\Omega\text{m}$ , measured in laboratory) caused a homogeneous drop of the resistivity values (as much as 100  
 284  $\Omega\text{m}$  difference) around plant B. The observed resistivity decrease in the upper 40 cm can be attributed to the presence of a

285 porous layer, and correspondingly fast infiltration. A similar drop can be seen for the plant A (Fig. B1). This is an indirect  
 286 evidence that water infiltrated in both areas (that are next to each other) with no difference in soil hydraulic properties. For the  
 287 time after irrigation, it is difficult to appreciate the change in resistivity from the absolute values while -time-lapse inversion  
 288 ([Error! Reference source not found.](#)<sup>4b</sup>) shows that the main increase in ER (up to 140% of the background value), was  
 289 located in the upper layers (< 0.3m depth) and occurred between the background time and T<sub>3</sub>. Note that the acquisition time  
 290 T<sub>3</sub> corresponds to the morning of the following day, since no measurement were taken overnight, and the acquisition time  
 291 match with the start of the increase of ET and mean air temperature. No increase was observed on plant A (Fig. B1). After T<sub>3</sub>,  
 292 no positive change in ER was observed.

### 293 3.2 Background and irrigation time steps of MALM measured data

294 Figure 5 shows the raw results of MALM acquisition on plant B, during background and irrigation, for both soil and stem  
 295 injection configurations. Note that voltages are normalized against the corresponding injected current. For both surface and  
 296 borehole electrodes the normalized voltage distribution can be compared against the one expected from the solution for [a single](#)  
 297 [current electrode, idealized as](#) a point injection of current  $I$  at the surface of a homogeneous soil of resistivity  $\rho$ :

$$298 \quad V = \frac{I\rho}{2\pi r} \quad . \quad (4)$$

299 where  $r$  is the distance between the (surface) injection point and the point where voltage  $V$  is computed (see Fig.5e for a  
 300 comparison). In all cases, both for surface and borehole electrodes, and both for stem and soil current injection, the [voltage](#)  
 301 [resistance](#) patterns are deformed with respect to the solution of Eq. (34) for a homogeneous soil. Some pieces of evidence are  
 302 apparent from the raw data ~~already~~:

- 303 a. In all cases, the pattern of surface and subsurface [voltage-resistance](#) is asymmetric with respect to the injection point  
 304 (in the stem or close to it, in the soil) and thus different from the predictions of Eq. (3); this indicates that current  
 305 pathways are controlled by the soil heterogeneous structure: note that at all times there is a clear indication that a  
 306 conductive pathway extends from the plant to the right-upper corner of the image (this would be the classical use of  
 307 MALM – identifying the shape of conductive bodies underground). Note that spatial variations of [voltage-resistance](#)  
 308 between boreholes are consistent with surface observations i.e. the maximum [voltage-resistance](#) was measured on the  
 309 borehole 4 located in the top right corner of the plot;
- 310 b. The [voltage-resistance](#) patterns in the case of stem injection are clearly different from the corresponding ones obtained  
 311 from soil injection. In particular, injecting in the soil directly produces a stronger [voltage-resistance](#) signal both at the  
 312 surface and in the boreholes than the corresponding [voltage-resistance](#) in the case of stem injection: this difference  
 313 clearly points towards the fact that the plant-roots system must convey the current in a different way than the soil  
 314 alone; tentatively the observed [voltage-resistance](#) features would indicate a deeper current injection in the case of  
 315 stem injection. Looking at the qualitative differences between soil and stem injection in the borehole electrode data,  
 316 the impact is very small at depths larger than 0.6m;
- 317 c. For both soil and stem injection, local anomalies observed in the background image are either removed or smoothed  
 318 during the irrigation steps. The effect is equally pronounced in soil and stem injection, showing that this is caused  
 319 essentially by the change in resistivity induced by the change in soil water content (see Fig.5).

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

323 **3.3 Inversion of virtual current sources to estimate roots extents**

324 Figure 6 shows the iso-surfaces of fitness index (or misfit)  $F_1$  (Eq. 2) for the background (pre-irrigation) conditions of plant B  
325 (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,  
326 Figure 6 shows the iso-surface corresponding to the value  $F_1 = 7V$  corresponding to the 25% misfit index (value selected after  
327 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  
328 provide comparable information for all cases. Note, nevertheless, that the position of the active roots from one acquisition to  
329 the other during the irrigation experiment (or for different seasons) may vary, so the distribution of the misfit and ultimately  
330 the depth of the iso-surface describing active roots.

331 In particular, the  $F_1$  procedure highlights the remarkable difference, for both plants A and B, between the injection in the stem  
332 and in the soil. Current injection in the soil produces a voltage distribution that, albeit corresponding to a heterogeneous  
333 resistivity distribution and thus different from the predictions of a simpler model such as Eq. (3), collapses effectively to one  
334 point, i.e. the point where current was effectively injected in the ground. On the contrary, when current is injected in the stem,  
335 the region of possible source locations in the ground is much wider, and depicts a volume that is likely to correspond to the  
336 contact points between roots and soil, i.e. the volume where roots have an active role in the soil especially in terms of RWU.  
337 While this latter interpretation remains somewhat speculative, at least in the present experimental context, nevertheless the  
338 different results between soil and stem injection can only find an explanation in the role of roots and their spatial structure.  
339 The most interesting feature shown by Figure 6 is that the likely source volumes do not change with time during irrigation  
340 except for the irrigation time  $T_1$  for which the iso-surface extended slightly more at depth. Note that the  $F_1$  procedure makes  
341 use of the changing electrical resistivity distributions caused by infiltrating water (see Fig. 4) thus the result is not obvious, and  
342 indicates an underlying mechanism that is likely to be linked to the permanence of the roots structure over such a short time  
343 lapse.

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

350 **3.4 Electrical resistivity variations inside and outside the likely active roots zone**

351 Our assumption is that the region identified by MALM  $F_1$  for the background time corresponds to the RWU region. The inner  
352 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  
353 extent of the root zone are only minor (Fig. 6), it makes sense to evaluate the changes, as an effect of irrigation, in electrical  
354 resistivity within such stable estimated root zone. Figure—Figure 8 shows the ER variations of selected values in the zones  
355 outside and inside this estimated active root zone. It is apparent how irrigation causes a general decrease of electrical resistivity  
356 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  
357 for the two plants, the behaviour is similar. Then at the end of irrigation we observe, for both plants, that resistivity continues  
358 to decrease outside the root active region, while it increases slightly inside. This behaviour is consistent with the fact that inside  
359 the region we expect that RWU progressively dries the soil, while outside this region resistivity continues to decrease (overall)  
360 as an effect (probably) of water redistribution in the unsaturated soil.

361 **3.5 One-dimensional simulation of the infiltration**

362 Figure 9a shows, the variations of the simulated soil water content ( $\theta_{\text{simu}}$ ) with time for control points located at different depths  
363 (see Fig. 2 for the geometry) and Fig. 9b shows the comparison against the 3dimensional variations of ER transformed values  
364 to soil water content ( $\theta_{\text{ERT}}$ ). Time steps of the ERT acquisition for starting time and end time are reported [on Fig. 9a](#) for an  
365 easier comparison [between the two figures with Fig. 9b](#). At  $T_0$ , values of soil water content are about 0.1, a value close to field  
366 capacity for this type of soil, as previously assumed (section 2.2) and in agreement with the literature. Despite all the  
367 assumptions and models' limitation described later, the range of soil water seems also consistent between the simulation and  
368 the measured data. Note also that the dynamic is closely linked to the estimated ET and mean air temperature shown in Figure  
369 2. The start and end time of the triggered irrigation are clearly identified respectively with a sharp increase following by a  
370 decrease of  $\theta_{\text{simu}}$  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  
371 by the irrigation front resulting in the increase of soil water content both visible in  $\theta_{\text{simu}}$  and  $\theta_{\text{ERT}}$  (Fig.9b). The infiltration front  
372 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  
373 soil water content overnight in the top 40cm soil. Time  $T_3$ , coincident with an increasing ET and mean air temperature,  
374 highlights a rupture from a slow decrease to a higher decrease rate particularly for the soil surface (the layer <0.2m depth), in  
375 agreement with the observed changes in  $\theta_{\text{ERT}}$  (Fig. 9b). Overall, Figure 9a and Figure 9b shows a good correlation between the  
376 dynamics of SWC changes predicted by the hydrological model ( $\theta_{\text{simu}}$ ) and observed via the ER transformed values ( $\theta_{\text{ERT}}$ ).

377 **4 Discussion**

378 The survey was carried out during a sunny summer season in a non-irrigated vineyard of the Bordeaux Region. The site is  
379 composed of sandy-loamy soil, thus there is a high infiltration rate during the experiment, and this would make it more difficult  
380 to distinguish RWU zones from infiltration zones as done for instance by Cassiani et al. (2015) using time-lapse ERT alone.  
381 The first objective of the study was to define a non-invasive investigation protocol capable of "imaging" the root activity as  
382 well as the distribution of active roots under varying soil water content. We demonstrated that the key additional information  
383 is provided by MALM which directly incorporates the ERT information in terms of changing electrical resistivity distribution  
384 in space including its evolution in time. MALM, and particularly its double application of current injection in the stem and in  
385 the soil next to it, uses electrical measurements in a totally different manner: here the plant-root system itself acts as a  
386 conductor, and the goal is to use the retrieved voltage distribution to infer where the current injected in the stem actually is  
387 conveyed into the soil: these locations are potentially the same locations where roots interact with the soil in terms of RWU.  
388 However, in order to try and locate the position of these points, it is necessary to know the soil electrical resistivity distribution  
389 at the time of measurements. At this scale of measurements, ERT provides 3D images of electrical resistivity distribution in  
390 the subsoil housing the root system. Fast acquisition allows the measurement of resistivity changes over time, which in turn  
391 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  
392 changes mapped through resistivity changes can be used to map the regions where roots exert an active suction and reduce  
393 SWC. However, water redistribution in the soil also plays a role in terms of resistivity changes. Thus some additional  
394 independent information about the location of active roots in the soil may help: this is the first coupling between ERT and  
395 MALM that has been integrated in the workflow. Considering the inverted MALM data as non-sensitive to soil water  
396 distribution has different potential useful impacts: the separation of contributions of root zone and outer area on ER values  
397 extracted from ERT help distinguish between soil processes such as RWU and hydraulic redistribution (hydraulic lift in  
398 particular).

399 Time-lapse ERT measurements gives clear evidence that injecting current in the stem and in the soil close to the stem produces  
400 different inversions even under changing soil water conditions. The soil injection produces a current density close to a punctual

401 injection (located at the true single electrode location) whatever the soil water content. The stem injection helps identify a 3D  
402 region of likely distributed current injection locations, thus defining a region in the subsoil where RWU is likely to take place.  
403 The latter result is particularly useful, in perspective: when computing the time-lapse changes of electrical resistivity inside  
404 and outside this tentative RWU region during irrigation we clearly see that while inside resistivity increases (as an effect of  
405 RWU, as irrigation is still ongoing), outside resistivity decreases. Thus, our assumption that the region identified by MALM  
406 inversion (albeit very rough) corresponds to the RWU region is corroborated indirectly also by this evidence.  
407

#### 408 **4.1 Comparison between geophysical data and hydrological model**

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

#### 418 **4.2 Recommendation for future experiments**

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

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

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

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

439 **5 Conclusions**

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

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462 **Data availability**

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

464

465 **Authors contributions**

466 GC, YW, and SH worked on the conceptualization of the research. BM curated the data. LP, BM, NC and JB collected the  
467 data. BM prepared the formal analysis, designed and wrote the scripts for carrying out the simulation and inversion, and ran  
468 the obtained the results. MS and GC supervised the field work. All the authors discussed the results. BM prepared the paper  
469 with contributions from all the authors.

470 **Competing interests**

471 The authors declare that they have no conflict of interest.

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

| Acquisition no.   | Plant | Starting time (LT) | Ending time (LT) | Irrigation                                    | Date                    | <u>% of data retained (10% reciprocs)</u> | Final RMS (Ohm.m) |
|-------------------|-------|--------------------|------------------|---|-------------------------|---|-------------------|
| 0 (background)    | A     | 10:20              | 11:00            | 13h00 to 15h30,<br>104lh-1<br>For both plants | Day 1<br>(19 June 2017) | <u>79464</u>                              | 1.15              |
|                   | B     | 12:20              | 13:00            |   |                         | <u>91496</u>                              | 1.76              |
| 1<br>(Irrigation) | A     | 15:00              | 15:30            | 13h00 to 15h30,<br>104lh-1<br>For both plants | Day 1<br>(19 June 2017) | <u>504277</u>                             | 1.54              |
|                   | B     | 13:30              | 14:00            |   |                         | <u>684721</u>                             | 1.31              |
| 2                 | A     | 17:00              | 17:30            | 13h00 to 15h30,<br>104lh-1<br>For both plants | Day 1<br>(19 June 2017) | <u>694747</u>                             | 1.36              |
|                   | B     | 18:00              | 18:45            |   |                         | <u>574459</u>                             | 1.50              |
| 3                 | A     | 10:30              | 11:00            |   |                         | <u>594516</u>                             | 1.72              |
|                   | B     | 9:30               | 10:00            |   |                         | <u>802048</u>                             | 1.24              |
| 4                 | A     | 14:00              | 14:30            |   | Day 2<br>(20 June 2017) | <u>724835</u>                             | 1.38              |
|                   | B     | 15:00              | 15:30            |   |                         | <u>802029</u>                             | 1.53              |
| 5                 | A     | 18:00              | 18:30            |   |                         | <u>704780</u>                             | 1.23              |
|                   | B     | 17:00              | 17:30            |   |                         | <u>784990</u>                             | 1.28              |

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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)

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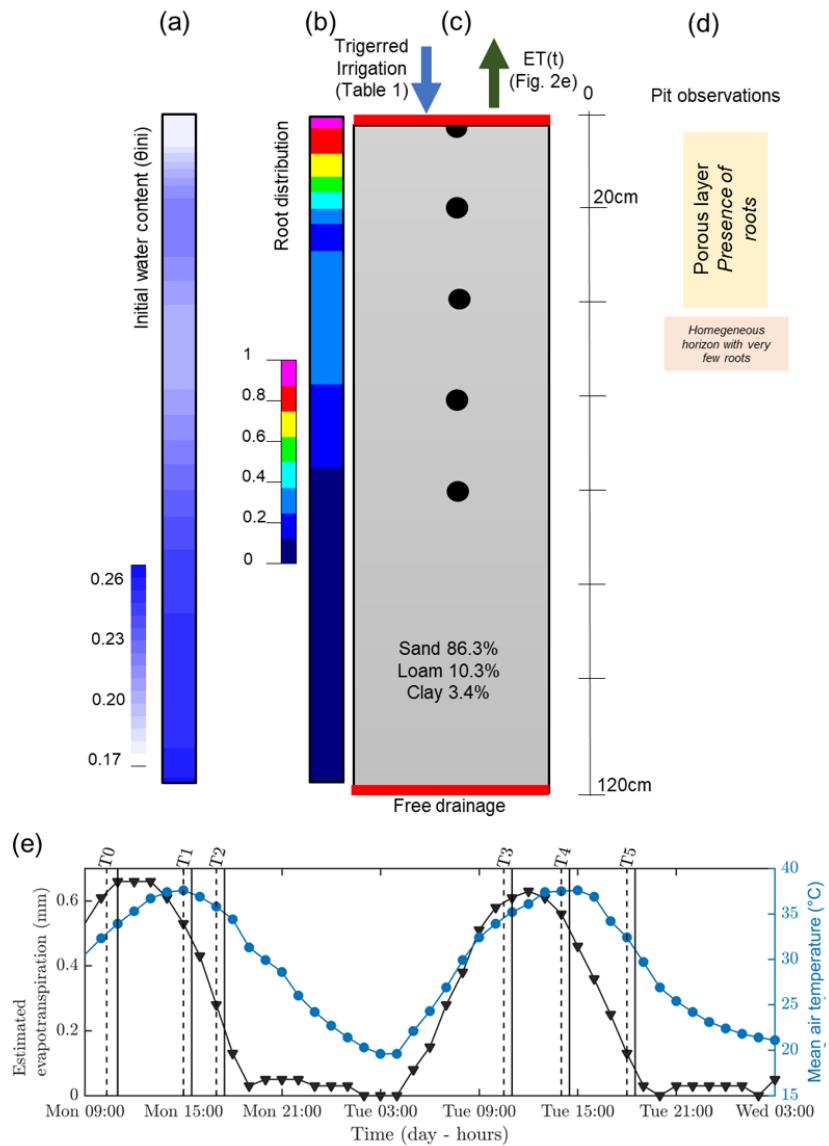
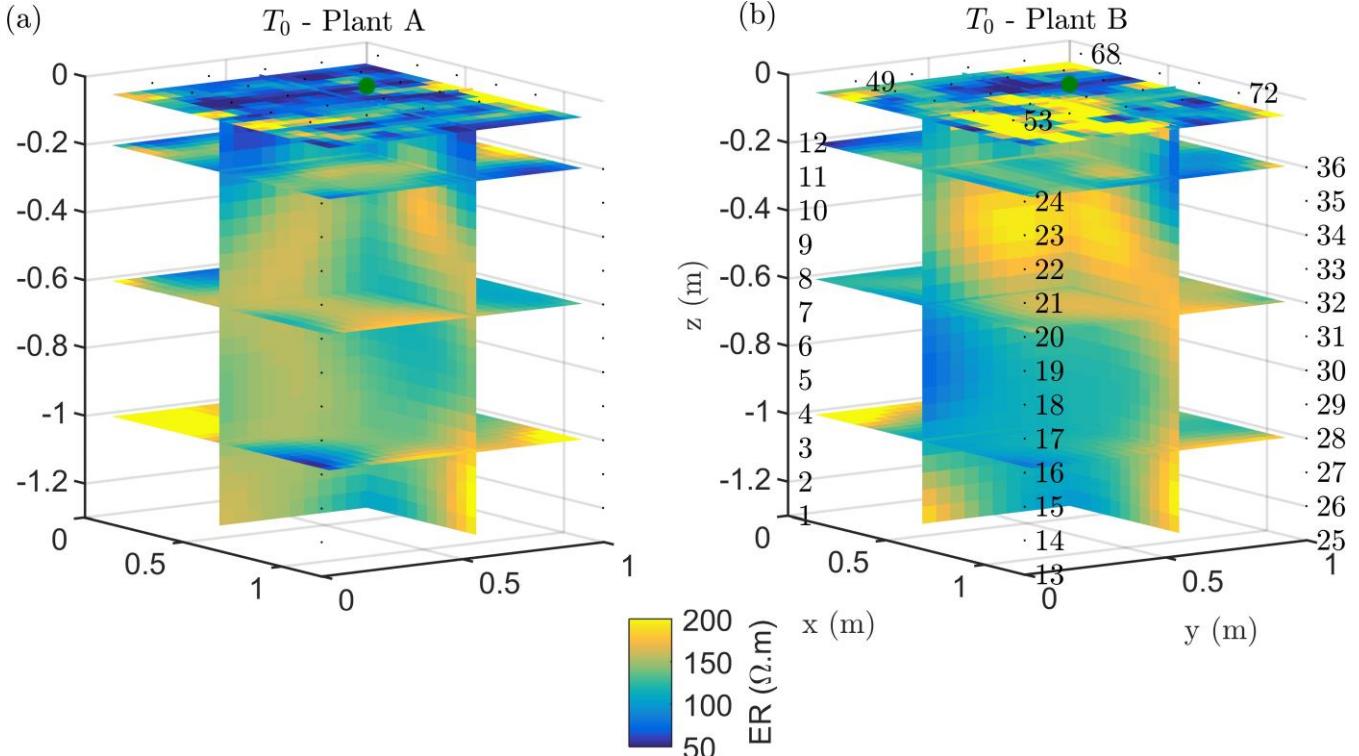
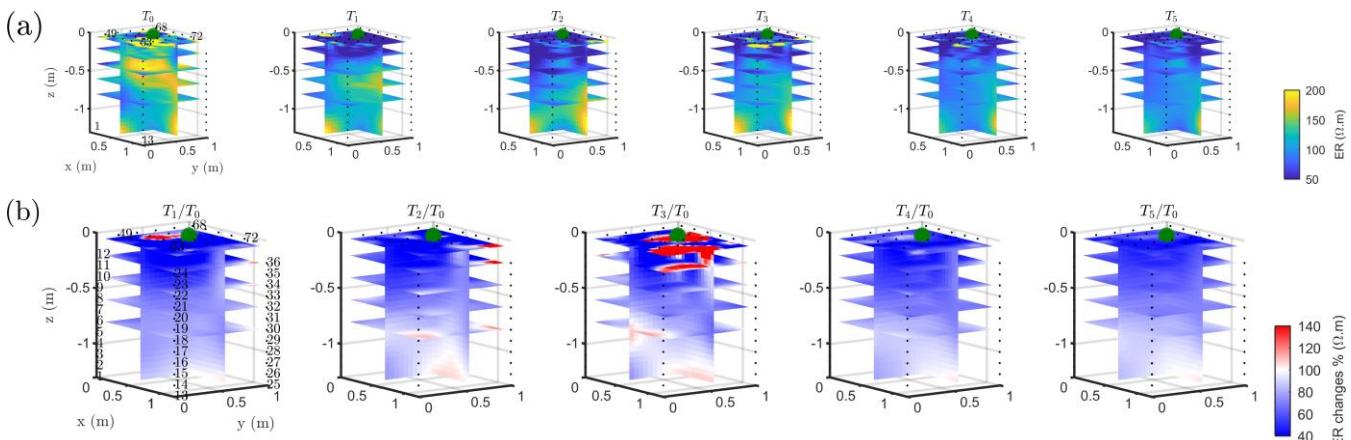


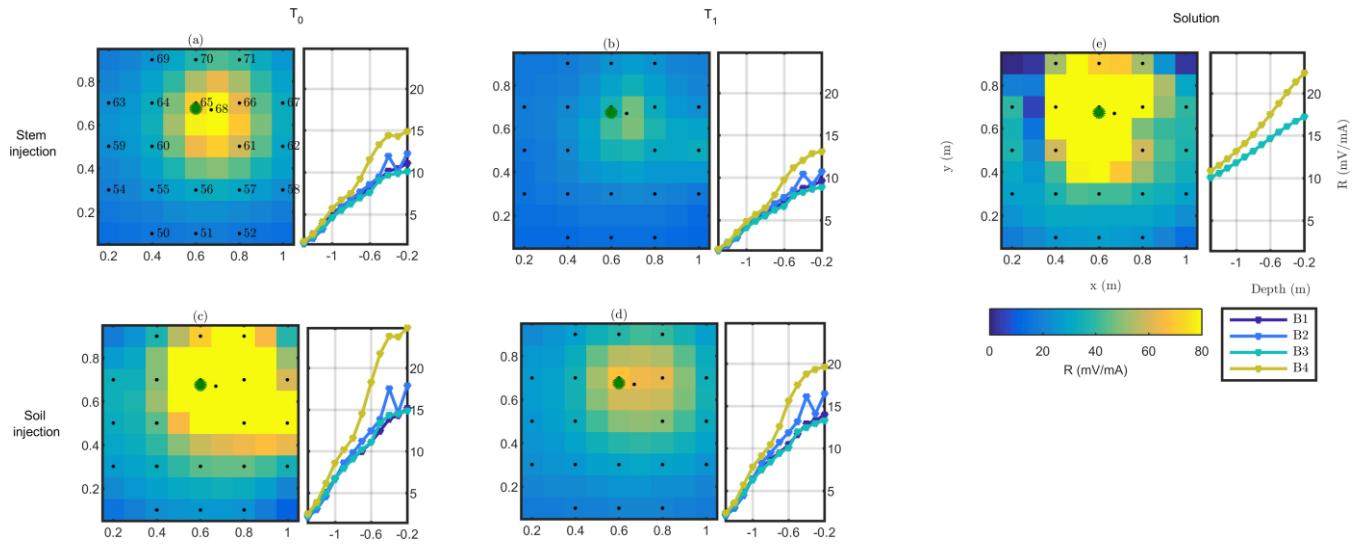
Figure 2: Initial (a,b,c) and time varying atmospheric conditions (e) used the hydrological simulation (e). From left to right (a-d), initial conditions on soil water content  $\theta_0$ , root density (1/cm), soil type, and pit observations. (e) variation of temperature (blue line) and estimated evapotranspiration (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).



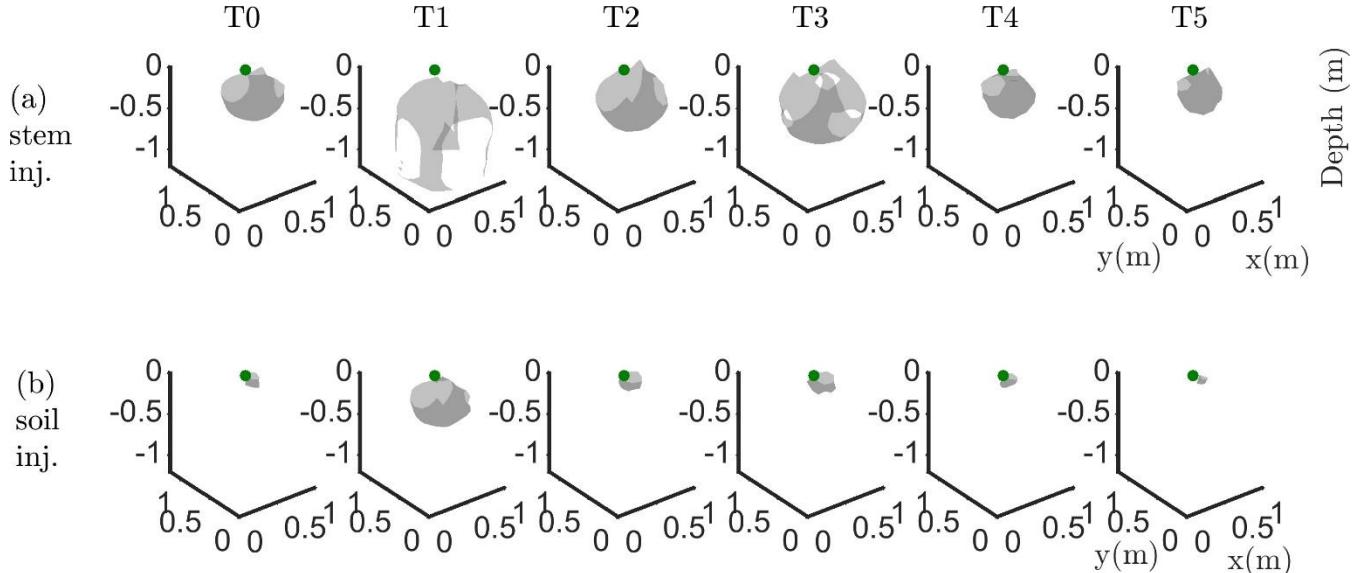
630 **Figure 3: Results of the 3-D ERT inversion for the background time  $T_0$  for plant A (a) and B (b). 3-D resistivity volume (log scale)**  
 631 **sliced at the tree stem position (vertically) and at four depths (0.05, 0.2, 0.6 and 1m), with the green point showing the location of the**  
 632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



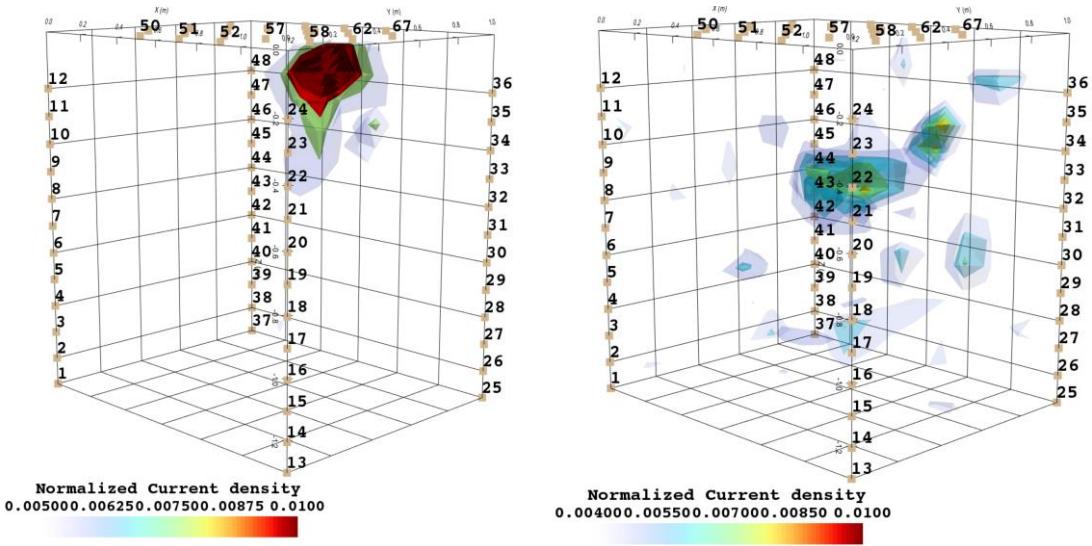
637 **Figure 4: 3D ERT results for plant B (plant A, in appendix Fig. B1). The volume is sliced at the tree stem position (vertically) and at**  
 638 **five depths (0.05, 0.2, 0.4, 0.6 and 0.8 m). (a) 3D inversion of the resistivity (in  $\Omega \cdot m$ , log scale) from the background time  $T_0$ , during**  
 639 **irrigation  $T_1$  and after irrigation. (b) time-lapse inversion (following Cassiani et al., 2006) showing the ratios (in % of ER changes)**  
 640 **between time step  $T_i$  and background time  $T_0$  (100% in white means no change).**



644 **Figure 5: plant BA, MALM results showing variations in surface (horizontal plan) of resistance  $R$  (in mV/mA) for the initial state**  
 645 **background  $T_0$  (a,c) and irrigation  $T_1$  (b,d)**  **steps. Comparison between the stem injection (a,b) and soil injection (c,d). The**  
 646 **black points show the surface electrodes loc**  **. The green point shows the positions of the plant stem. Data are filtered using a**  
 647 **threshold on reciprocal acquisition of 20%. (e) shows the solution using eq. (4) for a homogeneous soil of 100 Ohm.m; The resistance**  
 648 **between boreholes B1/B3 and B2/B4 (see legend) are identical and cannot be distinguished graphically in the case of (e).**



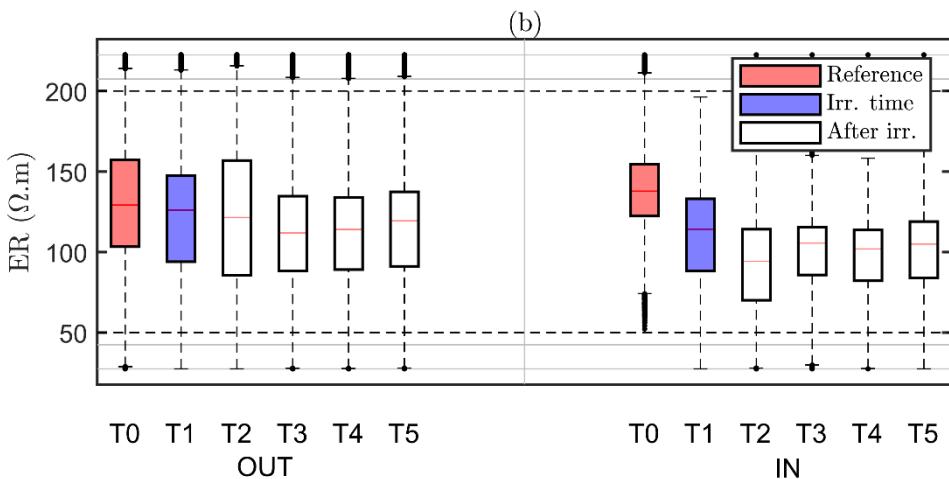
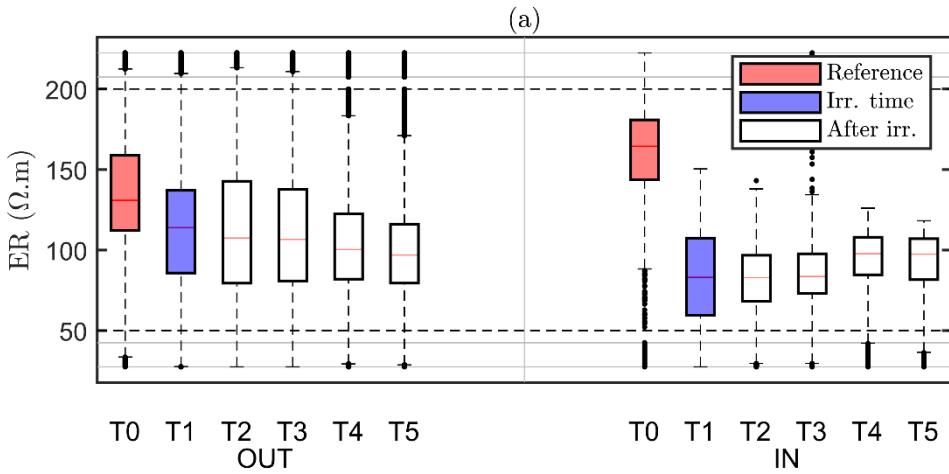
652 **Figure 6: iso-surface minimizing the  $F_1$  function for plant B; during stem injection (a), during soil injection (b); Columns represent**  
 653 **the six times steps from  $T_0$  to  $T_5$ . Green dot shows plant stem position. Threshold is defined by the misfit 25% of the normalised  $F_1$**   
 654 **(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**  
 655 **for all the time steps).**



659 **Figure 7: current source density after minimization of the objective function  $F_2$  as defined in Eq. (3). The results are relevant to the**  
 660 **background time  $T_0$  for the plant B, for the soil current injection (left) and the stem current injection (right).**

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666 Figure 8: boxplot distribution of ER time variations observed on the plant A (top) and plant B (bottom), for the values selected  
 667 outside (OUT, left part) and inside (IN, right part) of the region defined by the  $F_1$  best fit sources (see Fig. 6a-T<sub>0</sub>). The central mark  
 668 indicates the median, the bottom and top edges of the box indicated the 25th and 75th percentiles of ER data, respectively. The  
 669 whiskers extend to the most extreme data points (black dots) considered outliers. Each box corresponds to a given time step (see  
 670 table 1), indicated in the x-axis.

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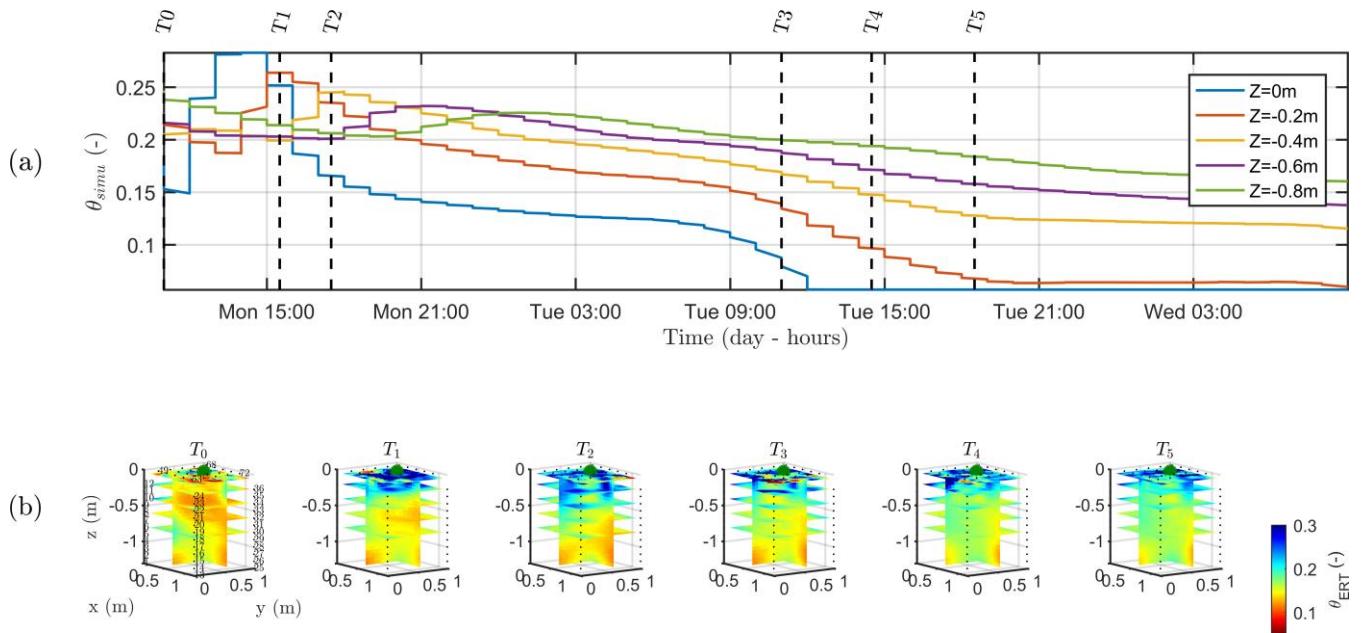
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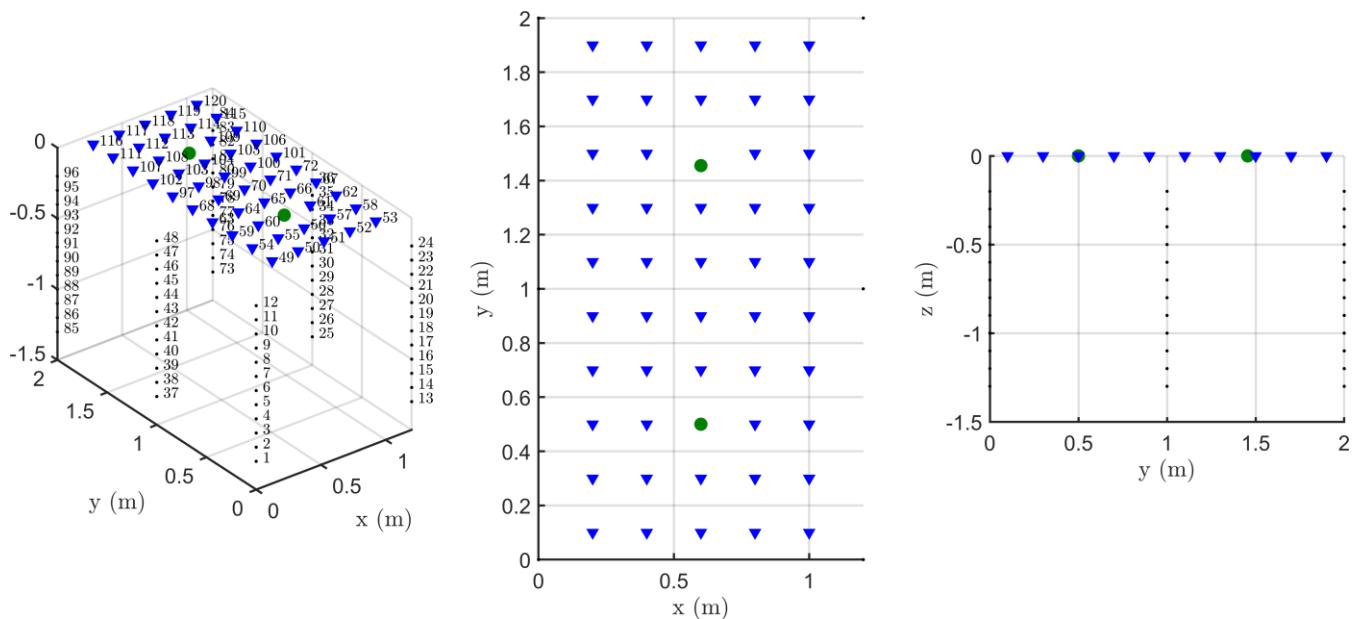
Figure 9: (a) time variation of simulated soil water content ( $\theta_{simu}$ ) at five depths. The vertical lines indicate the geophysical acquisition times (dashed and plain line respectively for the start and the end of the measurement, see Table 1). (b) 3D variations of the ERT-derived soil water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

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684 **Appendix A: set-up description**

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



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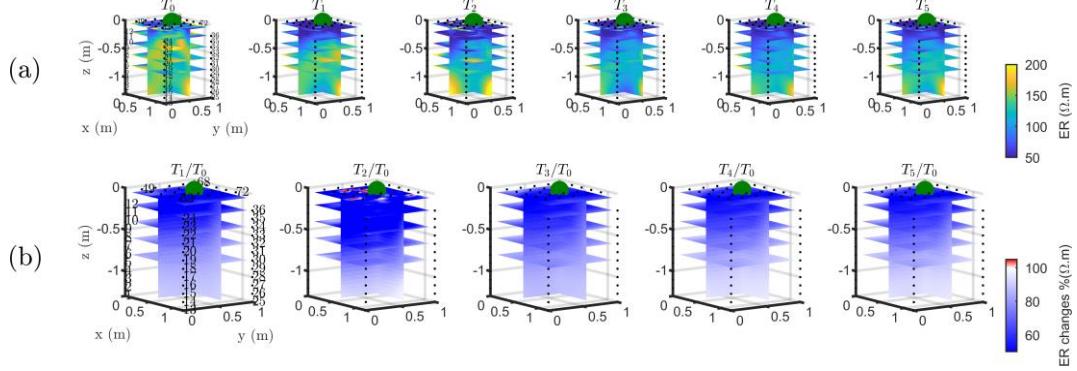
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690 **Appendix B: ERT monitoring**

691

692 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, 693 0.4, 0.6 and 0.8 m). (a) 3D inversion of the resistivity (in  $\Omega\text{m}$ , log scale) from the background time  $T_0$ , during irrigation  $T_1$  and 694 after irrigation. (b) time-lapse inversion (following Cassiani et al., 2006) showing the ratios (in % of ER changes) between 695 time step  $T_i$  and background time  $T_0$  (100% in white means no change).

696



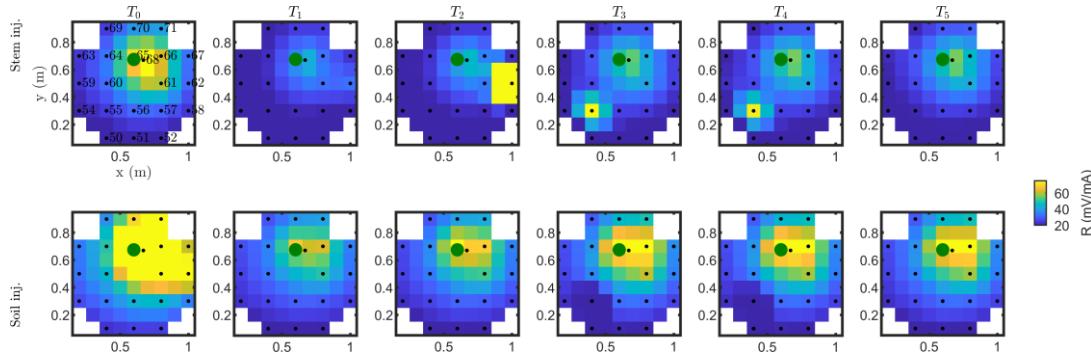
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698

699 **Appendix C: MALM monitoring**

700

701 Fig. C1: Voltage-Resistance distribution of the raw data of MALM time lapse monitoring for the plant B. First line results are 702 relevant to the stem injection while second line refers to the soil control injection. Columns describe time evolution according 703 to Table 1.

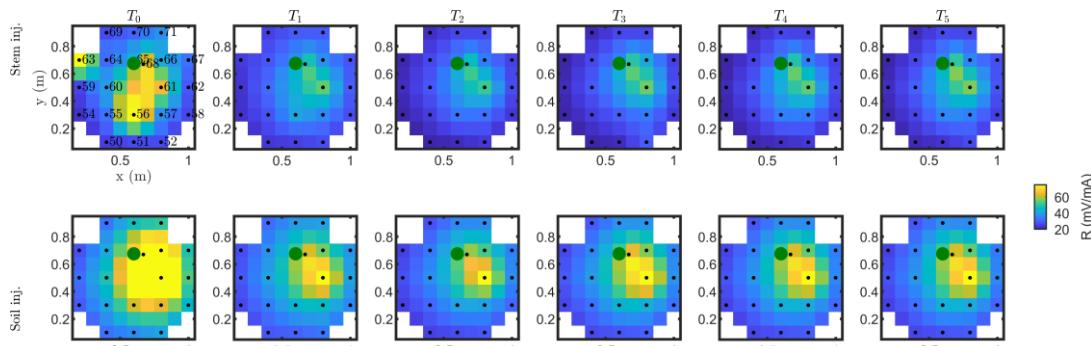


704

705

706

707 Fig. C2: Voltage-Resistance distribution of the raw data of MALM time lapse monitoring for the plant A. First line results are 708 relevant to the stem injection while second line refers to the soil control injection. Columns describe time evolution according 709 to Table 1.



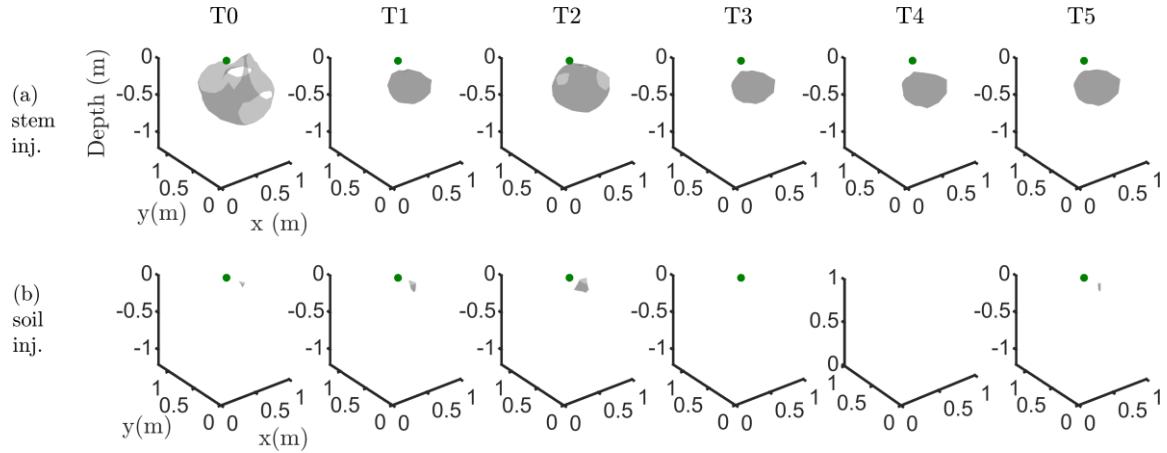
710

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

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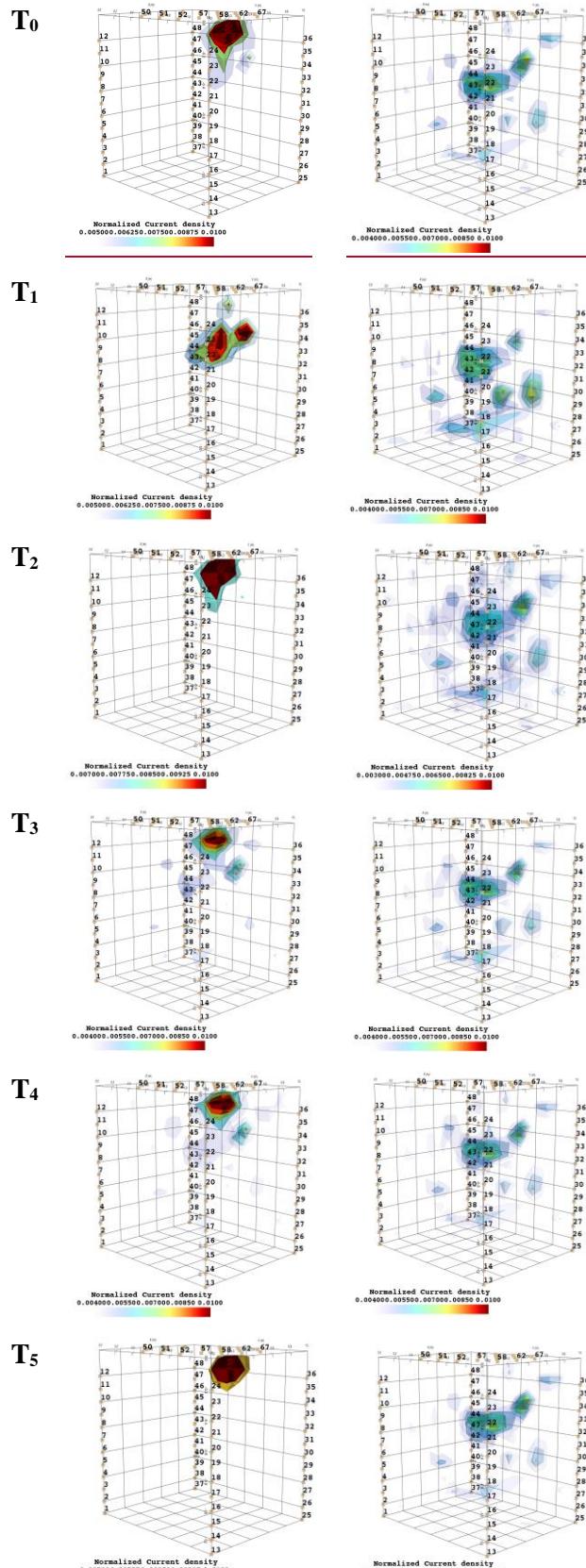
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719

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

723

### Soil injection      Stem injection



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