Reply to reviewer’s comments on manuscript

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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

by

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We thank the Reviewers and the Associate Editor for their positive and constructive comments. A detailed response to the comments is presented below. For the sake of clarity, the comments from the Reviewers are shown in *italic*, the authors’ replies are in **bold**.

Response to the Editor’s comments

Editor Initial Decision: Reconsider after major revisions (13 Feb 2015) by Prof. Marnik Vanclooster

The discussion on your manuscript has now been closed. The two imposed referee's and the additional free comment raised a large set of concerns. Some of those can be addressed in a revised version of the paper, others (e.g. validation of root extraction patterns by means of isotopic tracer data or allelometric measurements) cannot be addressed or are beyond the scope of your study. In your answers, you suggested how the concerns raised by the referees will be addressed in a revised version of the manuscript. I therefore propose to proceed with this revision, taken into consideration these suggestions. I propose you also to add to this revised version a report explaining how the different concerns have been addressed (largely based on the responses to the previous discussions of course).

We have taken all comments into considerations and implemented the relevant actions, where appropriate. See below the detailed report of how all concerns have been (or sometimes have *not* been) addressed.

Response to Referee #1 - T. P. A. Ferre

This is a very well considered hydrogeophysical investigation of soil-plant interactions in the root zone. The authors have collected a wide range of data, allowing for a clear interpretation of the value of geophysics for inferring root zone processes. In some cases, I think that their choices could simply be stated with less defense of their decisions to shorten the paper. But, in general, the work is presented clearly. I will review the main messages that I took from the paper and then make a suggestion for revision below.

The authors have conducted a 3D ERT survey of water content changes over a two day period, including an irrigation event. The found that water content changes could be described adequately as 1D, vertical. They conducted laboratory analyses of soil hydraulic properties and assumed that they were constant throughout the domain. Similarly, they established a single universal pedotransfer function for the domain. Finally, they assessed the depth of the root zone based on observations of the time lapse data (and a somewhat unclear discussion regarding limiting the uptake to a restricted zone). WIth these restrictions, they fitted observed changes in ERT-inferred water contents with depth to model results with only one free parameter - the surface of the root zone.

We thank Dr. Ferre for his appreciative evaluation and constructive comments. The summary he provides is correct.

The fit of the best model to the data is generally good. But, the lack of fit below 40 cm seems to indicate that the soil hydraulic properties imposed do not fully represent the system. Given the generally recognized difficulty of measuring soil hydraulic properties in the lab for field predictions, I would be tempted to allow some of the hydraulic parameters to vary during inversion, too, to get a better fit.

This suggestion is definitely worth considering. We feel that is will be interesting to assess how the uncertainty related to hydraulic parameters propagates into the uncertainty of the estimated RWU zone extent. We ran some sensitivity analysis in this direction but we immediately realized that a more complete sensitivity analysis concerning the impact of the individual parameters should be performed in a complete Monte Carlo manner in order to exclude identification trade-offs between the Van Genuchten parameters, the depth of the water table (known with some uncertainty) and the fluxes from irrigation, precipitation and evapotranspiration in conjunction to the effective 3D spatial distribution of active roots. This is currently the subject of ongoing research, and hopefully we shall be able to report the results soon (a presentation will be given at the upcoming EGU General Assembly in Vienna, April 2015.

The preceding is a small detail. My larger concern is that the interpretation, in terms of an area involved with root water uptake, does not seem strongly supported. Isn't the rate of uptake a combination of root density and per-root uptake rate? That would seem more physically reasonable than assuming a constant rate of uptake with only some of the soil participating. Similarly, I would not necessarily expect constant root water uptake from each depth. Perhaps the authors reported the root density versus depth and I missed it. At a minimum, the authors could use HYDRUS with depth dependent root water uptake as a clearer representation of root processes. All of this is meant

to encourage the authors to tighten up the interpretations related to root processes.

This is a key remark that concerns the general approach we take when assigning the RWU to a certain depth range. We acknowledge that assuming a uniform RWU rate distributed along the top 40 cm, with zero uptake below, is a simplified approach.

On the other hand, we strongly believe that the target here is precisely to provide the simplest explanation for the observed data, or better, for ALL observed data. This is in accordance to the principle of parsimony that shall underlie all scientific endeavours.

Note also that the parsimonious approach we take for modelling is consistent with the simplification adopted by averaging the ERT data along horizontal planes, thus reducing the analysis to a 1D problem. Given this approach, it would probably be pointless to try and infer the root density distribution only as a function of depth, while the 3D distribution around the tree is likely to be as, if not more, important.

We are also confident that we could, of course, introduce more complex root density distributions with depth (but still concentrated largely in the top 40 cm!) and still obtain practically the same simulated 1D moisture content distribution, provided the total water extracted is maintained the same.

In a nutshell: we feel that either we should pursue a full 3D approach leading to an inversion towards the identification of root uptake density (far beyond the scope of this paper), or we should stick to the presented simplified (an yet very informative!) approach.

This is a strong and unique data set that should help to establish hydrogeophysics in a relatively new field. It would be great to make sure that people in that field see information presented in a context that will speak clearly to them!

We have revised the presentation to make it as clear as possible.

Finally, I would ask the authors to make a special effort to demonstrate the value of the geophysical data. It would require an additional set of analyses, but it would be very helpful to try to interpret (with uncertainties reported) the root uptake with and without the ERT data. How much more can you say (or how much more accurately can you say it?) Again, it would be great to be able to point to this article when we want to make a quantitative case for including geophysics in root zone monitoring efforts!

The suggestion is conceptually interesting. We should try and demonstrate the value of the ERT data by presenting an attempt of estimating RWU without this data. However it is in the particular case at hand this should be done changing the modelling scheme from 1D to 3D (or at least axial-symmetric), as the TDR data we have available are at a certain distance from the tree trunk, and thus (likely) at the margin of the root water uptake zone. Alternatively one could assume that the TDR data are representative of a 1D vertical distribution of moisture content in the citrus orchard – this indeed would not be totally without sense if we did not have ERT data.

In the revised version of the discussion we added some specific comments in this direction, along the lines suggested by the Referee.

Response to Referee #2

GENERAL COMMENTS

Cassiani et al. presented a very nice data set combining several techniques to close the water balance of an irrigated orange tree: ERT, sap flow, eddy covariance data, soil physical data; and to calibrate and validate ERT data under field conditions: TDR, pore water conductivity, petrophysical relationship for changing soil moisture content, . . .

The aim of the paper is to characterize the volume of the active root zone of the orange tree by coupling a Richards-type model with the experimental data and calibration for the root zone. I appreciate the completeness and quality of the data set, which is far from evident under field conditions. The coupling of data and model in this context is also an important attempt which has often been tried by researchers, but rarely worked out or was very simplified.

We thank the referee for his/her positive general comments. He/she also provides a number of specific remarks that we feel must be addressed in detail, as shown hereafter:

Even though I think this work can be very interesting and innovative in this field of research, the authors still have to improve

(1) their description of the used methodologies, especially for the modeling part. I did not find any specification on the equations used, especially for the sink term in the Richards equation. Based on the information in the paper, it is very difficult to understand how you can calibrate a volume of root water uptake with a 1-D equation, etc. This really must be explained more systematically. The calibration and validation approach, statistical decision tools, etc. should be discussed.

We agree with the referee: in the revised version of the paper we have given all the necessary details, including a new figure (Figure 9) explaining the geometry of the system.

(2) the use of the model outcomes. Next to the active root zone, results on sink term distribution and soil water fluxes based on the coupling of data and model should be given.

Some more detail on the results of the 1D modelling will be given in the revised paper. However it is not totally clear to us what the reviewer is actually questioning here.

In addition, I do not understand why the authors limit the paper to a two day period, whereas in the M&M part they speak of an experiment on much longer term. . . Next to the daily cycle, the dynamics over the growing season are of main interest in this context!

The paper presents results derived from both short term (2 days) and long term monitoring. The micrometeorological data set (including the measurements of the energy balance components) and the sap flow data are available since 2009. ERT measurements were carried out only during a 2-day period, but the state of the system at the time of the ERT measurements clearly depends on the past forcings acting on the system. The entire dataset is therefore used when data and simulations are compared.

Explicit description of how both long and short term data are used was reported at page 13, lines: 278-283 of the revised manuscript

(3) the authors explain in detail their setup to measure ET using an eddy-covariance tower, but I do not see where they use these data afterwards in the paper. As explained now, I understood that only the sap flow data are used as a forcing for the model.

This remark is correct. Indeed in the modelling itself we only used sap data, as they are directly and uniquely attributable to the single orange tree we monitored. However we feel that the comparison between sap flow data of transpiration and Eddy Covariance fluxes allows for a better understanding of diurnal plant dynamics with respect to the microclimate of the study area. However, in order to clarify the role we attribute to EC data in this paper, we removed Fig.2 from the revised version of the paper, and we reduced the length of the EC data description. Please see at page 9, lines: 194-207 of the revised manuscript.

DETAILED COMMENTS

P 13354 l 8: this is the only place where 4-D inversion appears. If you use this term, please give more information in the M&M part on the type of inversion constraints put on the time dimension, since they can highly influence the result.

We agree with the comment. We used "time-lapse" rather than 4D in the Abstract

P 13355 l1 irrigated water that/which is not taken up

Ok, see at page 3, line 47

P 13355 l15-27 This part is a bit unsatisfactory. There are two options, either you do not speak of this at all, since anyhow, you do not aim to test several model types in this paper, if I understand well; either you included some more recent literature and other authors to make this more complete and up to date. See recent papers of Valentin Couvreur, Mathieux Javaux, Tiina Roose, . . . Recent literature shows for example that there is a mathematical link between the two categories you propose and that they are not that different finally.

We agree and we modified this part of the paper. Please see at page 4, lines 76-78

P13357 l 10-13: As this is the main focus of your paper, I would be more complete on the existing literature applying ERT to characterize root water uptake and root system characterization. (You could deleted some of the general papers before, to gain space if necessary) More specifically, I would also like to see an *indication of lab and field studies, since they have different focus and outcomes. Also studies on woody plants and agricultural crops could be differentiated here, because mainly the influence on the petrophysical relationship seems to be different for these two categories. Therefore I suggest adding the papers of e.g. Beff et al. 2012, Amato 2009, Michot 2003, Garré 2011,2012, Cassiani 2012, . . . If the groups of Binley and/or Kemna already published*

some of their work on the effect of roots on soil electrical properties, this would also need to be added here (however, of these two I am not sure if there is already some formal paper).

We agree, and we expanded the literature review as suggested. Please see at page 5, lines 113-116 and page 6, line 117-118

P 13358 l 15 mean leaf area index => over space AND time?

The LAI values are spatially averaged and are referred to the ERT measurement period (October 2013). In the specific case of a mature orange orchard, LAI values are fairly constant in time in the region of interest. These details are specified in the revised version of the paper. Please see at page 7, lines 148-150

P 13358 l22 Ks with falling head permeameter => specify how many replicates, variation of result-

ing values, . . .

We have 32 K_s measurements over the study site; we will add some details in the revised version of the paper. These details are specified in the revised version of the paper. Please see at page 7, lines: 154-163 and page 8, lines: 164-172

P 13358 l 26 reflectomeTErs?

Ok, see at page 8, line 173

P 13358 – 13359 Is it possible to make a scheme of the field with the location of all sensors relevant to the data presented in this paper with respect to the tree rows etc?

We also feel that a scheme is needed. We have included a Figure 9 in the text in order to clarify the sensor distribution around the investigated tree. The tree falls within the micrometeorological station footprint area. Please see at Figure 9 of the revised manuscript.

P 13359 l 5 why did you adopt this setup with horizontal and vertical TDRs? How did you install them exactly, especially the horizontal ones?

The TDR probes location is considered well suited with the specific characteristics of the micro-irrigation system used in the area and the textural soil main features. Specifics about TRD installation were included at page 8, lines: 173-184

P 13359 l 17 Something that strikes me in the paper is the different time scales of the various data sources: eddy covariance since 2009, sap flow ??, TDR ??, ERT only 2 days in 2013. Can you specify this better in the beginning of the paper and also explain why this is so different. For example, why do you only have two days of ERT data. If you have a specific reason for this, state it more clearly in the objectives of the paper.

Here again we acknowledge that in the original paper the different use of the data was not explained in sufficient detail. See our reply to major comment number (2) of this same referee. Please see at Results section, page13, lines:278-283

P 13359-13360 Some things need to be specified more clearly to ensure reproducibility of the research:

P 13360 l 2 CSAT3, I suppose. I may be wrong but, to my knowledge, CSAT3 is a sonic and not a gas analyser. I think thus that information about the GA is lacking. Especially, it's important to specify if it's an open path (type LI-COR 7500) or a closed path (type LI-COR 7000 or 6262). Each system requires specific corrections. On the photograph in Figure 1 I can see the IRGA at intermediate height: that's a LI-COR 7500 open path. Higher, I see a sonic sensor but no IRGA. . .

P 13360 l 10 That's a little bit short : you should give more info about flux computation procedure

and corrections : how do you cope with high frequency attenuation (in closed path), with rain periods (if open path)? Do you apply the Webb Pearman Leuning (WPL) correction (if open path)? Do you apply a *stationarity screening for data filtering? Eddy covariance computation packages cannot be used as black boxes. They must be parameterised in taking the system specificities into account.*

The open path infrared absorption gas analyser is a LI-7500 from LI-COR. The eddy covariance measurement system and the data processing followed the guidelines of the standard EUROFLUX rules (Aubinet et al., 2000). A data quality check was applied during the post processing together with some routines to remove the common errors: running means for detrending, three angle coordinate rotations and despiking. Stationarity and surface energy balance closure were also checked (Kaiman and Finningan, 1994). These details were added at page 9, lines: 203-209 and page 10, lines: 210-2012

P 13360 l 16 This is a quite good result that probably validates the whole method.

Agreed

P 13360 l 19 Why the choice for the HPV technique, since it seems to be more and more abandoned by the community due to difficulties to find the 0 flow point. Please specify this.

Heat-pulse techniques can be used to measure sap flow in plant stems with minimal disruption to the sap stream (Swanson and Whitfield, 1981; Cohen et al., 1981; Green and Clothier, 1988). The measurements are reliable, use inexpensive technology, provide a good time resolution of sap flow, and they are well-suited to automatic data collection and storage. Sequential or simultaneous measurements on numerous trees are possible, permitting the estimation of transpiration from whole stands of trees. We added some details to this end in the revised manuscript. Please see at page 10, lines: 224-229

P13361 -13362 For the ERT M&M part add answer to following questions in the text: - what was the material and size of the buried, mini- and stick-electrodes? - how was the borehole made and good electrode contact ensured? How did you minimize hydraulic disturbance due to the vertical holes or if you didn't can you comment on the extent of disturbance of the flow field? - Did you arbitrarily choice the electrode configuration (based on some general characteristics) or you conducted some virtual or real field tests prior to the experiment. If yes, please give some info on that. - If I understand well, you have no measurements between sticks, only along the sticks? - An image of sensitivity distribution of the configuration for a homogeneous medium would be interesting to evaluatethe set-up. - Which ERT device did you use for the measurements. - What kind of error model did you use and how did you obtain it? Or did you just put a constant error and if yes, is it the average value of all timeframes and all electrodes? The *data quality seems good, especially under complex field conditions, so that's positive. – Specify which constraint was used for the timelapse inversion (time dimension).*

Many of the details requested here are already in the paper. But just to clarify: the electrodes are made of stainless steel, plates 3cm high and wound around the PVC pipe. The boreholes were made by percussion with the help of a pre-drilling with a smaller diameter in order to avoiding the disturbance of the electrical flow. A similar setup was used by Boaga et al., (2013). The electrical contact is excellent for all 48 buried electrodes, as checked before each measurement. The 4 boreholes are water tight and in tight contact with the soil, so they cannot act as pathways for preferential water infiltration. In addition, we focused our attention to an area slightly smaller that the square defined by the boreholes, in order to avoid the inevitable disturbance caused by borehole installation (indeed, slightly compacting the surrounding soil). There are also 24 surface electrodes, and this covers partly the region between the boreholes. Note however that by its own nature ERT is NOT a LOCAL measurement. We used an IRIS Syscal Pro resistivimeter for all measurements. Sensitivity distribution is well known from the literature (e.g. Binley and Kemna 2005) and there is no need to repeat these concepts specifically in this paper. The error model is described in Binley and Kemna 2005 for the error level chosen here (10%, as specified already). All other details of the inversion have been published in a number of papers using the same inversion codes (all in http://www.es.lancs.ac.uk/people/amb/Freeware/freeware.htm). The time lapse inversion is a ratio inversion, already described in the paper and relevant literature is referred to (e.g. Cassiani et al., 2006). We revised the ERT description in the paper to make sure that the overall picture is clear.

Figures 5 and 6: I have the impression the color scales are not optimally chosen to see the variability in the 3-D images. I think images in log scale or EC instead of resistivity would show more. Figure 6 is really not readable. Scales are too small.

We modified the Figure 6 (now Figure 5) to make it much more readable. On the contrary, we disagree concerning the colours.

P13363 l5 You refer to fig 6 here, but it is not clear at this point how you obtained the 'EC derived total ET'. Please explain.

It is of course derived from the EC measurements. We do not quite understand what the referee is asking for at this point.

P 13363 l 20-25 I particularly like the fact that you checked the effect of pore water salinity, an parameter that is often neglected, as you state yourself. However, could you specify with which frequency, which method of pore water extraction, where in the field, etc.?

We used laboratory suction cups for water extraction from the soil samples. We added details at page 14, lines: 315-319

P 13364 l 5: Can you detail the experimental protocol? Did you wash the samples several times with the solution to obtain homogeneous pore water concentration? What was the sample size? Figure 7: why don't you show all data?? I they fall on top of each other, the image should remain readable and the value of the graph would be much higher. . . Could you also show the fit you decided to use to convert rho in WC in the same graph?

We added some of these details in the paper. The procedure for testing the soil samples is similar to the one in Cassiani et al. (2009).

p 13365 l17 This would be a really interesting case-study indeed. Looking forward to that piece of work.

☺

P 13365 l 21 I see the importance and interest of coupling model and data, but I do not know why you have to throw away all the 3-D information to be able to do it. . . In that case, you could simply have put a vertical profile of TDRs and use that data as a source for the model. This would have been cheaper and faster. . .

The wealth of information in the time-lapse 3D has not been fully exploited using the 1D simulation, but the information is anyway much more abundant than the one that can be derived from a few scattered TDR probes.

P13366 l 1 I think you should clearly split, both in M&M and in Results, experimental considerations and modeling considerations, in order not to loose the reader.

This comment is not clear to us. We have anyway tried to improve the paper readability in the direction of splitting model and measurement descriptions.

*P 13366-13367 Here I was lost and I am still not sure whether I understood correctly. For example, how can you find a volume of active roots if you use a 1-D model? If it were real 1-D, the transpiration rate (T_act) measured in units of L/T could be directly used and only the depth of the root system would matter. Is this what you did? The authors considered that the average horizontal area per tree (dˆ2, where "d" is the average distance between trees) is larger than the horizontal area the root systems have access to (rˆ2 < dˆ2). Thus the tree water uptake is concentrated in a relatively small volume and the horizontal soil moisture is quite heterogeneous. If at this point the authors still use 1-D simulations, they probably considered no horizontal capillary flow between the regions outside and inside of rˆ2. This has a direct implication on flow boundary condition which has to be taken in a "horizontally smaller" 1-D domain. The volumetric transpiration rate per tree being T_act*dˆ2 (in units of Lˆ3/T), the uptake rate per tree in a 1-D domain of horizontal area rˆ2 has to be T_act*dˆ2/rˆ2. In other words, considering that the root system doesn't have access to the water lo cated outside of its area, the smaller the area, the more concentrated the 1D uptake rate, with a ratio dˆ2/rˆ2. I think this is not quite intuitive and not well explained in the manuscript. The hypothesis of no horizontal capillary flow between the outside and inside of the root zone can also be questioned and needs to be clearly specified.*

The referee captured the essence of our approach, so to some extent we must have been able to explain it. However we agree that some more effort must put in clarifying this matter. The plot given above in this reply is a step forward and we used a similar figure in the revised manuscript. Note however that we do not fully neglect horizontal capillary flow ! Indeed this flow explains the TDR data (Figure 9). However there is no doubt that at the TDR location moisture content is MUCH higher than closer to the tree, therefore horizontal flow is not such an efficient mechanism in the water migration at this site.

P 13366 l 5 which are the relevant parameters? Further in the text I find the retention curve parameters, but nothing on how you parameterized the sink term. . . In addition, you give no information on how these parameters were obtained. You state on the one hand that main variations are vertically, but on the other hand several characteristics of the field site make that you can expect 2-D surface heterogeneity: drippers, tree plantation (row-interrow), . . . Did you choose your ERT measurement area so small as to eliminate these horizontal heterogeneities?

The relevant parameters are, of course, the ones described in the Van Genuchten model. The sink term is NOT a parameter, rather a boundary condition, that is described as a prescribed flow term. As for the predominant 1D pattern observed at the site: this is clearly supported by the ERT data both in the long

and short term (figs 5 and 6). We chose the ERT setup to image the soil around the tree, and TDR proves that important variations occur beyond the extent of the ERT control volume.

In p13367 l 10 you use the TDRs to validate some results, but on the other hand here you speak of heterogeneity yourself. Why aren't the TDRs installed in the same measurement area as the ERT with respect to the tree (even another tree would have been possible).

The TDR had been installed previous to the design of the ERT experiment. We do not use the TDR to validate the ERT results, but we highlight how the evidence of the two setups concur to provide a consistent picture of the system's behaviour as shown by the integration of data and modelling.

P 13368 l 1 you speak of lateral forces.

We speak of capillary forces. The referee's comment is unclear to us.

Response to Jaivime Evaristo

This paper by Cassiani et al. proposes an exciting and novel approach to utilizing multiple soil-plant-atmosphere measurement techniques, not only for qualifying depth of plant water uptake but also for (spatially) quantifying root water uptake (RWU) activity. Well-written and concise, the authors very clearly reviewed our state-of-knowledge, as well as knowledge gaps, with respect to modeling plant water use strategies. Indeed, that RWU dries the soil is not a discovery. It is rather the ability to quantify soil moisture variability (due to RWU) – and using this understanding to inform and calibrate root zone hydrological models – that presents the greatest opportunity for new technological and analytical methods in this area. Of noteworthy contribution from this work is the potential widespread utility of using time-lapse 3D ERT for monitoring soil moisture content distribution as it relates to transpiration and micrometeorological data.

We thank Mr. Evaristo for his positive comments.

These favorable comments notwithstanding, I urge the authors to address the following general comments before the work may be considered for publication: 1) Perhaps, a "hallmark" of techniques in plant water uptake studies is stable isotope tracing. While it is not my intention to impinge upon the authors' liberty to *use methods of their preference (i.e. ERT and sap flow), their finding that RWU was greatest at 0.40m might be reinforced if stable isotope tracing methods (e.g. δ2H) also showed the same. There are at least 120 published papers that demonstrated the usefulness of stable isotope tracing methods (δ2H, δ18O or both) in plant water uptake studies. If the authors could demonstrate that their ERT-sap flow method agrees with stable isotope methods, then their (0.4m-depth) finding, in my view, may be regarded as unequivocal. In order to advance our state-of-knowledge in RWU studies, I am of the opinion that it is incumbent upon the new methods/approaches (like the one proposed by Cassiani et al.) to demonstrate "comparability" with what the broader community may regard as "state of practice" (i.e. stable isotopes). 2)Results of this work imply that the orange tree used water from a certain depth (~0.4m) more than any other depth in the volume.*

We also appreciate the reader's constructive criticisms. In particular we acknowledge that it is fair to introduce some reference to the use of stable isotopes. We will make sure the final paper reports some comments on this. However we would also like to warn the readers about putting too much confidence on stable isotope analysis alone. This is not a new method in hydrology (it may be in root uptake studies) and it is known to depend strongly on assumptions about full mixing water contributions that, in turn, cannot be verified. The modelling itself of mixing in the unsaturated zone is not by any means established on sound basis. Therefore conclusions based solely on stable isotopes have the unpleasant characteristic of being extremely local (they are only point measurements) and heavily based on unverified assumptions. However, we strongly believe that stable isotopes in conjunction with other methods can give a fundamental contribution to the understanding of water mixing and provenance studies.

The authors, however, failed to provide possible mechanisms (1) with which water at this depth is being replenished, either from direct percolation from shallower or from capillary rise from deeper parts in the profile; and, (2) for water uptake bias at this depth, i.e. is this related to root length density, root biomass, mycorrhizal fungi density, etc.? For example, Kurz-Besson et al. (2006) in a similar Mediterranean setting in south Portugal showed that the largest amount of fine roots are found in the top soil at 0.2 m depth (~ 20% of total root biomass), while between 13 and 17% of total root biomass are found in deeper layers at 0.4 and 0.9 m. Using stable water isotopes, they found that plant water uptake was consistent with water from 0.4-0.9 m depth. Using the same method, they were also able to demonstrate how hydraulic lift and redistribution (Dawson 1993) plays a significant role in this system. While the combined ERT-sap flow method of Cassiani et al. has the benefit of high spatial resolution, it is almost impossible to pin down the actual mechanisms of soil-plant water flow without the use of tracers (like stable water isotopes). Given that the ERT-sap flow method of Cassiani et al. holds promise for better quantification of water fluxes in soil-plant interactions (at a tree level), how these fluxes vary using their method at a stand level and higher are still unknown. Although this can form part of future work, it is imperative that the authors provide explicit statements acknowledging the limitations of their method within the broader context of what other existing methods can resolve in soil-plant-atmosphere studies.

We do not quite agree with the complaint that "the authors, however, failed to provide possible mechanisms…" regarding (1) water replenishment of the root zone and (2) water uptake at the maximal RWU depth.

In fact, our simplified 1D modelling clearly shows the prevalence of the replenishment from surface irrigation (we acknowledge though that this point was not specifically addressed in the paper – we will add some detail in this respect).

As for point (2), we acknowledge that the specific structure of the root system that is producing the enhanced RWU at the depth of interest was not in the focus of our attention. We rather envisaged the soil-plant-atmosphere as one system and we focussed on understanding its overall functioning. We believe that all mechanisms put forward by the reader (root length density, root biomass etc) may indeed contribute. An analysis in this direction would, however, require destructive testing that we were not ready or indeed willing to perform at the selected study site.

A few other specific points should be addressed:

1) *P13359-60: ". . .the sum of sensible and latent (LE) heat flux is highly correlated. . ." Much of the paper focused on ERT-sap flow, less on the value that the EC data provided. For example, Fig. 2 is supposed to illustrate something about the site and its value to modeling tree-level measurements. However, nothing was mentioned regarding Figure 2, and related EC measurements as they relate to the overarching research question, after these pages.*

P13359-60: we acknowledge this. Indeed the EC data have not been really used in this work – rather they are provided for comparison against the sap data (Figure 6). Therefore we agree we removed some of the details given in the first version of the paper, including Figure 2.

2) *P13366: Photos of the site do not seem to qualify as having a "dense canopy cover", which partly forms the basis for neglecting direct evaporation from the square meter of soil around the stem. Before ruling out direct evaporation, it may be appropriate to use leaf area index (LAI) values, and make use of their Eddy Covariance data to test whether direct evaporation is worth neglecting. Soil physics work has shown that evaporation is controlled, in series, by both hydraulic continuity (via capillary action) and vapor diffusion mechanisms. The latter mechanism, albeit characterized by low evaporation rates, has been shown to be independent of atmospheric forcing. The authors are referred to a review by Or et al. (2013) for a more comprehensive approach to modeling soil evaporation.*

P13366: canopy coverage is indeed very dense – the photo provided may not render justice to reality – especially along the tree rows. LAI values are around 4 m^2/m^2. We added this detail now in the revised paper. Please see at page 7, lines: 148-150

3) *P13367: That soil moisture is much higher than in ERT-controlled block closer to the tree is not surprising. It implies a zone of low soil moisture around the tree, understandably linked to water withdrawal by the plant. Bejan et al. (2008) - Unifying constructal theory of tree roots, canopies and forests – showed scaling relationships between total water mass flow rate and tree length, as well as between tree length and wood mass, among others. Can Cassiani et al. test and show possible relationships between various tree dimensional metrics and their actual ERT-sap flow data? The good agreement between theoretical models (like those of Bejan et al.) and empirical data may provide a potentially powerful premise for upscaling this work's tree-level results to stand level predictions. The authors can perhaps begin with the simple question: Does 0.75 m from the stem of the tree correspond to the radial extent of the crown?*

P13367: this is a good idea, even though definitely beyond the scope of this paper.

Supporting materials

1) Kurz-Besson, C. et al. Hydraulic lift in cork oak trees in a savannah-type Mediterranean ecosystem and its contribution to the local water balance. Plant Soil 282, 361-378 (2006)

2) Dawson, T. Hydraulic Lift and Water Use by Plants: Implications for Water Balance, Performance and Plant-Plant Interactions. Oecologia 95,565-574 (1993)

3) Or, D., Lehmann, P, Shahraeeni, E., Shokri, N. Advances in soil evaporation physics-A review. Vadose Zone Journal 12. (2013)

4) Bejan, A., Lorente, S. Lee, J. Unifying constructal theory of tree roots, canopies and forests. J Theor Biol 254(3):529-40 (2008)

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.

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Abstract

Mass and energy exchanges between soil, plants and atmosphere control a number of key environmental processes involving hydrology, biota and climate. The understanding of these exchanges also play a critical role for practical purposes e.g. in precision agriculture. In this paper we present a methodology based on coupling innovative data collection and models in order to obtain quantitative estimates of the key parameters of such complex flow system. In particular we propose the use of hydro-geophysical monitoring via "time-lapse" Electrical Resistivity Tomography (ERT) in conjunction with measurements of plant transpiration via sap flow and evapotranspiration from Eddy Covariance (EC). This abundance of data is fed to spatially distributed soil models in order to characterize the distribution of active roots. We conducted experiments in an orange orchard in Eastern Sicily (Italy), characterized by the typical Mediterranean semi-arid climate. The subsoil dynamics, particularly influenced by irrigation and root uptake, were characterized mainly by the ERT setup, consisting of 48 buried electrodes on 4 instrumented micro boreholes (about 1.2 m deep) placed at the corners of a square (about 1.3 m in side) surrounding the orange tree, plus 24 mini-electrodes on the surface spaced 0.1 m on a square grid. During the monitoring, we collected repeated ERT and TDR soil moisture measurements, soil water sampling, sap flow measurements from the orange tree and EC data. We conducted a laboratory calibration of the soil electrical properties as a function of moisture content and pore water electrical conductivity. Irrigation, precipitation, sap flow and ET data are available allowing knowledge of the system's long term forcing conditions on the system. This information was used to calibrate a 1D Richards' equation model representing the dynamics of the volume monitored via 3D ERT. Information on the soil hydraulic properties was collected from laboratory and field experiments. The successful results of the calibrated modelling exercise allow the quantification of the soil volume interested by root water uptake. This volume is much smaller (with a surface area

less than 2 square meters, and about 40 cm thickness) than expected and assumed in the design of classical drip irrigation schemes that prove to be losing at least half of the irrigated water which~~that~~ is not uptaken by the plants.

Keywords: Hydro-geophysics; Soil moisture; ERT, Eddy Covariance; Sap Flow; Root-zone.

1. INTRODUCTION

The system made of soil, vegetation and the adjacent atmosphere is characterized by complex patterns, structures, and processes that act on a wide range of time and space scales. While the exchange of energy and water is continuous between compartments, the pertinent fluxes are strongly heterogeneous and variable in space and time and this makes their quantification particularly challenging. Plants are known to impact the terrestrial water cycle and underground water dynamics through evapo-transpiration (ET) and root water uptake (RWU). The mechanisms of water flow in the root zone are controlled by soil physics, plant physiology and meteorological factors (Green et al., 2003a). The translation of plant water use strategies into physically-based models of root water uptake is a crucial issue in eco-hydrology and has fundamental consequence in the understanding and modelling of atmospheric as well as soil processes. Still, no consensus exists on the modelling of this process (Feddes et al., 2001; Raats, 2007). From a conceptual point of view, two main approaches exist today, which differ in the way of predicting the volumetric rate of RWU.

A first approach expresses water transport in plants as a chain process based on a resistance law. Coupled with a three-dimensional soil water flow model, this approach leads to fairly accurate RWU models at the plant scale (Doussan et al., 2006; Schneider et al., 2010), also under water stress conditions. The limitations of these models are the cost of characterizing parameters, such as root system architecture and conductance to water flow, and their computational demand. A second approach, mostly used in soil-vegetation-atmosphere transfer models, relies on "macroscopic parameters" and predicts RWU as a product of the potential transpiration rate, a spatially distributed root parameter (e.g. relative root length density), and a stress function, depending on soil water potential and a compensatory RWU function (Jarvis, 1989). The major drawback of this approach is the necessity to calibrate the macroscopic parameters, which introduces substantial uncertainties (Musters and Bouten, 2000). Note that the two approaches have indeed some formal links with each other (Couvreur et al., 2012; Javaux et al., 2008).

The complexity of RWU modelling is highly related to the uneven root distribution in the vertical and radial directions (Gong et al., 2006). This variability is partly induced by heterogeneities in the soil and localized soil compaction caused by both cultivation and irrigation patterns (Jones and Tardieu, 1998) that in turn cause heterogeneous water and nutrient distribution. Consequently, there is a clear need for the development of novel RWU modelling approaches (Couvreur et al., 2012; Feddes et al., 2001; Raats, 2007; Jarvis, 2011;~~ Couvreur et al., 2012~~), as well as for accurate measurements techniques of soil water content and RWU dynamics.

In particular, soil moisture measurements are of paramount importance to calibrate RWU models. Traditionally, and especially beneath irrigated crops, soil moisture has been determined using methods such as neutron probes, TDR or capacitance systems. As these traditional techniques are point measurements, they do not provide sufficient information for reliable mass balance assessments; therefore our understanding of RWU as a spatially distributed system remains fundamentally limited. In this respect the understanding of soil as a spatially heterogeneous system shares fundamental limitations with most of earth sciences. Therefore much can be learnt looking at similar research fields.

Geophysical methods have long been established for the imaging of the soil subsurface at a variety of scales, from large scale mining exploration (e.g. Parasnis, 1973) to the very small scale of soil mapping (e.g. Allred et al., 2008). The past twenty years, in particular, have seen the fast development of techniques that are useful in identifying structure and dynamics of the near surface, with particular reference to hydrological applications. This realm of research goes under the general name of hydro-geophysics (Binley et al., 201; Rubin and Hubbard, 2005, Vereecken et al., 2006~~, Binley et al., 2011~~) and covers a wide range of applications from flow and transport in aquifers (e.g. Kemna et al., 2002; Perri et al., 2012) to the vadose zone (e.g. Daily et al., 1992), from catchment (e.g. Weill et al., 2013) and hillslope characterization (Cassiani et al., 2009a) to agriculture and eco-hydrological processes (Boaga et al., 2014; Ursino et al., 2014).

Possibly the most interesting results have been obtained when hydro-geophysical data have been coupled with distributed hydrological model predictions. The degree of integration of data and model range from trial and error calibration (e.g. Binley et al., 2002) to full data assimilation (e.g. Hinnell et al., 2010), but in all cases the availability of spatially extensive (and time intensive) data greatly improve the models' capability to identify within narrow ranges the relevant governing parameters, that in turn are of practical interest for hydrological predictions.

Relatively few hydro-geophysical applications, though, have been focussed on plant root system characterization (e.g. al Hagrey et al, 2007; al Hagrey and Petersen, 2011; Javaux et al., 2008; Jayawickreme et al., 2008, Werban et al., 2008), often limiting the analysis to a tentative identification of the main root location and extent. Electrical soil properties are a clear indication of soil moisture content distribution and electrical and electromagnetic methods have been used to identify the effect of root activity (e.g. Cassiani et al., 2012; Shanahan et al., 2015). In particular, ERT has been used to characterize root water uptake and root system (Garré et al., 2011; Michot et al., 2001; Michot et al., 2003; Srayeddin and Doussan, 2009). Amato et al., (2009; 2010) tested the ability of 3D-ERT for quantifying root biomass on herbaceous plants. Beff et. al., (2013) used 3D-

ERT for monitoring soil water content in a maize field during late growing seasons. Boaga et al., (2013) and Cassiani et al. (2015) demonstrated the reliability of the method in apple orchards.

In this paper we aim at applying hydro-geophysical techniques, with a combination of measurements and modelling, to a tree root system. This approach has, to the best of our knowledge, not been presented and analysed yet. In particular, we present the application of the time-lapse non-invasive 3D electrical resistivity tomography (ERT) to monitor soil-plant interactions in the root zone of an orange tree located in the Mediterranean semi-arid Sicilian (South Italy) context. The subsoil dynamics, particularly influenced by irrigation and RWU, have been characterized by the 3D ERT measurements coupled with plant transpiration through sap flow measurements. The information contained in the ERT measurements in terms of vadose zone water dynamics was exploited by comparing the field results against a 1-D vadose zone model.

The specific goals of this paper are

(a) to study the feasibility of a small scale monitoring of root zone processes using time-lapse 3D ERT;

(b) to assess the value of the data above for a quantitative description of hyrological processes at the tens of centimeter scale;

(c) to interpret these data with the aid of a physical hydrological model, in order to derive also information on the root zone physical structure and its dynamics.

2. SITE DESCRIPTION

~~*2.1 The Bulgherano experimental site*~~

The experiment was conducted in a 20-hectar orange orchard, planted with about 20 year-old trees (*Citrus sinensis*, cv Tarocco Ippolito) (Figure 1). The field is located in Lentini (Eastern Sicily, Lat. 37°16'N, Long. 14°53'E) in a Mediterranean semi-arid environment, characterized by an annual average precipitation of around 550 mm, very dry summers and average air temperature of 7°C in winter and 28°C in summer. The site presents conditions of crop homogeneity, flat slope, dominant wind speed direction for footprint analysis and quite large fetch that are ideal for micrometeorological measurements. The planting layout is 4.0 m × 5.5 m and the trees are drip irrigated with 4 in-line drippers per plant, spaced about 1 m, with 16 L h^{-1} of total discharge (4 L h^{-1} per dripper); the crop is well-watered by irrigation supplied every day from May to October, with irrigation timing of 5 h d^{-1}. The study area has a mean leaf area index (LAI) of about 4 m^2 m^{-2}, measured by a LAI-2000 digital analyser (LI-COR, Lincoln, Nebraska, USA). The LAI values are spatially averaged and are referred to the ERT measurement period (October 2013). In the specific case of a mature orange orchard, LAI values result fairly constant in time in the region of interest.

The mean PAR (photosynthetic active radiation) light interception was 80% within rows and 50% between rows; the canopy height (h_c) is 3.7 m.

The soil characterization was performed via textural and hydraulic laboratory analyses, according to the USDA standards. ~~, and it is classified as loamy sand. In this study we used *van Genuchten*'s (1980) analytical expression to describe soil water retention and a falling head permeameter to determine the hydraulic conductivity at saturation. For each soil sample, the moisture content at standard water potential values was determined by a sandbox and a pressure membrane apparatus (*Aiello et al.*, 2014).~~

The area, covered by mature orange orchards, was divided into regular grids, each having a 18 × 32 m^2 area, where undisturbed soil cores (0.05 m in height and 0.05 m in diameter) were collected at the 0-0.05 m and 0.05-0.10 m depths for a total of 32 sampling points and 64 soil samples. The undisturbed soil cores were used to determine the soil bulk density, ρ_b (Mg m^{-3}) and the initial water content, θ_i (m^3m^{-3}), i.e. the θ value at the time of the field campaign. A total of 32 disturbed soil samples were also collected at the 0-0.05 m depth to determine the soil textural characteristics using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium metaphosphate and mechanical agitation (Gee and Bauder, 1986). Three textural fractions according to the USDA standards, i.e. clay (0-2 µm), silt (2-50 µm) and sand (50-2000 µm), were used in the study to characterize the soil (Gee and Bauder, 1986). Most soil textures (i.e. 27 out of 32) were loamy sand and the remaining textures were sandy loam.

An undisturbed soil sample was collected from the surface soil layer (0-0.05 m depth) at each sampling location (sample size, *N* = 32), using stainless steel cylinders with an inner volume of 10^{-4} m^3 to determine the soil water retention curve. For each sample, the volumetric soil water content at 11 pressure heads, *h*, was determined by a sandbox (*h* = 0.01, 0.025, 0.1, 0.32, 0.63, 1.0 m) and a pressure plate apparatus (*h* = 3, 10, 30, 60, 150 m). For each sample, the parameters of the van Genuchten (1980, vG) model for the water retention curve with the Burdine (1953) condition were determined (Aiello et al., 2014).

Three soil water content profiles are measured in the field using water content reflectometers (TDR, ~~(~~Time Domine Reflectometry), since 2009.~~.~~ Calibrated Campbell Scientific CS616 water content reflectometers (±2.5% of accuracy) were installed to monitor every 1 h the changes of volumetric soil water content (Δθ). The TDR probe installation was designed to measure soil water content variations with time in the soil volume afferent to each plant. -The TDR probes location is considered well suited with the specific characteristics of the micro-irrigation systems used in the area and the textural soil main features. For each location the TDR equipment consists of ~~t~~two sensors inserted vertically at 0.20 and 0.45 m depth and of two sensors inserted horizontally at 0.35 m depth, with 0.20 m in between. The water content reflectometer consists of two stainless steel rods connected to a printed circuit board. When the probe rods were inserted vertically into the soil surface they gave an indication of the water content in the upper 20-25 cm of soil. The probes installed horizontal to the surface were used to detect the passing of wetting fronts of water fluxes.

The data that are discussed here (see results section) correspond to the TDR probes located at about 1.5 m from the orange tree we monitored with ERT.

Hourly meteorological data (incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall) are acquired by an automatic weather station located about 7 km from the orchard and managed by SIAS (Agro-meteorological Service of the Sicilian Region). For the dominant wind directions, the fetch is larger than 550 m. For the other sectors the minimum fetch is 400 m (SE).

3. METHODOLOGY

3.1 Micrometeorological measurements

The experimental site is equipped with Eddy Covariance (EC) systems mounted on a micrometeorological fluxes tower (Figure 1). Continuous energy balance measurements have been since 2009. In particular, ~~N~~net radiation (R_n, W m^{-2}) is measured with two CNR 1 Kipp&Zonen (Campbell Scientific Ltd) net radiometers at a height of 8 m. Soil heat flux density (G, W m^{-2}) is measured with three soil heat flux plates (HFP01, Campbell Scientific Ltd) placed horizontally 0.05 m below the soil surface. Three different measurements of G were selected: in the trunk row (shaded area), at 1/3 of the distance to the adjacent row, and at 2/3 of the distance to the adjacent row. The soil heat flux is measured as the mean output of three soil heat flux plates. Data from the soil heat flux plates is corrected for heat storage in the soil above the plates.

The air temperature and the three wind speed components are measured at two heights, 4 and 8 m, using fine wire thermocouples (76 μm diameter) and sonic anemometers (Windmaster Pro, Gill Instruments Ltd, at 4m, and a CSAT, Campbell Sci., at 8 m). A gas analyzer (LI-7500, LI-

COR~~CSAT, Campbell Sci.~~) operating at 10 Hz was installed at 8 m. The raw data are recorded at a frequency of 10 Hz using two synchronized data loggers (CR3000, Campbell Sci.).

The Eddy Covariance measurement system and the data processing followed the guidelines of the standard EUROFLUX rules (Aubinet et al., 2000). A data quality check was applied during the post processing together with some routines to remove the common errors: running means for de-trending, three angle coordinate rotations and de-spiking. Stationarity and surface energy closure were also checked (Kaimal and Finningan, 1994).

Low frequency measurements are taken for air temperature and humidity (HMP45C, Vaisala), wind speed and direction (05103 RM Young), and atmospheric pressure (CS106, Campbell Scientific Ltd) at 4, 8 and 10 m.

The freely distributed TK2 package (Mauder and Foken, 2004) is used to determine the first and second order statistical moments and fluxes on a half-hourly basis following the protocol used as a comparison reference described in Mauder et al. (2007). ~~Surface energy balance measurements at the experimental site show that the sum of sensible and latent (LE) heat flux is highly correlated (r^2>0.90) (Figure 2) to the sum of net radiation and soil heat flux (*Castellvì et al.*, 2012; *Consoli and Papa*, 2013). A linear fit between the two quantities show a certain energy balance un-closure. The percentage of un-closure (about 10%) is in the range reported by most flux sites (*Wilson et al.*, 2002) and provides additional confirmation of the turbulent flux quality (*Moncrieff et al.*, 2004).~~

3.2 Sap flow measurements

Heat-pulse techniques can be used to measure sap flow in plant stems with minimal disruption to the sap stream (Cohen et al., 1981; Green and Clothier, 1988; Swanson and Whitfield, 1981). The measurements are reliable, use inexpensive technology, provide a good time resolution of sap flow, and they are well-suited to automatic data collection and storage. Sequential or simultaneous measurements on numerous trees are possible, permitting the estimation of transpiration from whole stands of trees.

Measurements of water consumption at tree level (T_{SF}) have been taken using the HPV (Heat Pulse Velocity) technique that is based on the measurement of temperature variations (ΔT), produced by a heat pulse of short duration (1-2 s), in two temperature probes installed asymmetrically on either side of a linear heater that is inserted into the trunk. For HPV measurements, two 4 cm sap flow probe with 4 thermocouples embedded (Tranzflo NZ Ltd., Palmerston North, NZ) were inserted in the trunks of the trees, belonging to the area of footprint of the micrometeorological eddy covariance tower. The probes were positioned at the North and South sides of the trunk at 50 cm from the ground and wired to a data-logger (CR1000, Campbell Sci., USA) for heat-pulse control and measurement; the sampling interval was 30 min. The temperature measurements are obtained by means of ultra-thin thermocouples that, once the probes are in place, are located at 5, 15, 25 and 45 mm within the trunk.

Data have been processed according to Green et al. (2003b) to integrate sap flow velocity over sapwood area and calculate transpiration. In particular, the volume of sap flow (Q_{stem}) in the tree stem is estimated by multiplying the sap flow velocity by the cross sectional area of the conducting tissue. To this purpose, fractions of wood (F_M=0.48) and water (F_L=0.33) in the sapwood were determined on the trees where sap flow probes were installed. Wound-effect correction (Consoli and Papa, 2013; Green et al., 2003b; Motisi et al., 2012) was done on a per-tree basis. Crop transpiration data are available at the study site since 2009.

3.3 Electrical resistivity tomography (ERT)

The key technique used to monitor the soil moisture content distribution in the volume surrounding the orange tree is electrical resistivity tomography (ERT – e.g. Binley and Kemna, 2005). In particular, we installed a three-dimensional ERT system, consisting of 48 buried electrodes placed on 4 instrumented micro-boreholes, with 12 electrodes each (see Figure ~~3~~2). The electrodes are made of ~~a metal plate~~stainless steel wound around a one-~~-~~inch ~~plastic~~ PVC pipe, and are spaced 10 cm along the pipe (see inset in Figure 2~~3~~), thus the shallowest and the deepest are respectively at 0.1 m and 1.2 m below the surface. Each electrode is made of a plate 3 cm wide. The boreholes are placed at the vertices of a square, having a side of 1.3 m, that has the orange tree at its centre, and were inserted by percussion with the help of a pre-drilling with a smaller diameter in order to avoiding the disturbance of the electrical flow. The electrical contact is excellent for all 48 buried electrodes, as checked before each measurement. The 4 boreholes are water tight and in tight contact with the soil, so they cannot act as pathways for preferential water infiltration. We focused our attention to an area slightly smaller that the square defined by the boreholes, in order to avoid the inevitable disturbance caused by borehole installation (slightly compacting the surrounding soil). The system is completed by 24 electrodes at the ground surface, placed along a square grid of about 0.21 m side, covering the 1.3 m x 1.3 m square at the surface (Figure ~~4~~3): this setup allows a homogeneous coverage of the surface of the control volume. The chosen acquisition scheme was a skip-zero dipole-dipole configuration, i.e. a configuration where the current dipoles and potential dipoles are both of minimal size, i.e. they consist of neighbouring electrodes e.g. along the boreholes. This setup ensures maximal spatial resolution (as good as the electrode spacing, at least close to electrodes themselves) provided that the signal/noise ratio is sufficiently high. The data quality is assessed using a full acquisition of reciprocals to estimate the data error level (see e.g., Binley et al., 1995; Monego et al., 2010). Consistently, we used for the 3D data inversion an Occam approach as implemented in the R3 software package (Binley, 2014) accounting for the error level estimated from the data themselves. The relevant three-dimensional computational mesh is shown in Figure ~~4~~3. At each time step, about 90-95 % of the dipoles survived the 10% reciprocal error threshold. In order to build a time-consistent data set, only the dipoles surviving this error analysis for all time steps were subsequently used, reducing the number to slightly over 90% of the total. The absolute inversions were run using the same 10% error level. Time-lapse inversions were run at a lower error level equal to 2 % (consistently with the literature – e.g., Cassiani et al., 2006). We conducted repeated ERT measurements using the above apparatus for about two days, starting on October 2, 2013 at 11:00 am, and ending the next day at about 16:00. The schedule of the acquisitions and the irrigation times is reported in Table 1. Note that the background ERT survey was acquired on October 2 at 11:00 before the first irrigation period was started, so that all changes caused by irrigation and subsequent evapotranspiration can be referred to that instant. Note that prior to October 2, 2013, irrigation had been suspended for at least 15 days. Note also that only one dripper – with a flow of about 4 l/h – is located at the surface of the control volume defined by the ERT setup (Figure ~~4~~3).

4. RESULTS AND DISCUSSION

The paper presents results derived from both short term (2 days) and long term monitoring. The micrometeorological data set (including the measurements of the energy balance components) and the sap flow data are available since 2009. ERT measurements were carried out only during a 2-day period, but the state of the system at the time of the ERT measurements clearly depends on the past forcing acting on the system. In order to fully exploit the information content of this dataset, we aimed at comparing data against simulations, as much as possible in a quantitative manner.

The ERT monitoring as described in Table 1 produced two clear results:

(1) The initial conditions (11:00 a.m. of October 2, before irrigation starts) around the tree show a very clear difference in electrical resistivity in the top 40 cm of soil with respect to the rest of the volume (Figure ~~5~~4). Specifically, the resistivity of the top layer ranges

around 40-50 Ohm m, while the lower part of the profile is about one order of magnitude more conductive (about 5 Ohm m). As no apparent lithological difference is present at 40 cm depth (see also laboratory results below) we attributed this difference to a marked difference in soil moisture content. This was confirmed by all following evidence (see below).

(2) The resistivity changes as a function of time, during the two irrigation periods, during the night interval, and afterwards, all show essentially the same pattern, with relatively small (but still clearly measureable) changes (Figure ~~6~~5). Two zone are identifiable: (a) a shallow zone (top 10-20 cm) where resistivity decreases with respect to the initial condition; and (b) a deeper zone (20-40 cm) where resistivity increases.

Qualitatively, both pieces of evidence can be easily explained in terms of water dynamics governed by precipitation, irrigation and root water uptake. Specifically, the shallower high resistivity zone in Figure ~~5~~ 4 can be correlated to a dry region where root water uptake manages to keep soil moisture content to minimal values, as an effect of the entire summer strong transpiration drive. The dynamics in Figure ~~6~~5, albeit small compared to the initial root uptake signal in Figure ~~5~~4, still confirm that the top 40 cm is house to a strong root activity, to the point that irrigation cannot raise electrical conductivity of the shallow zone (10-20 cm) by no more than some 20%, and the roots manage to make the soil even drier (with a resistivity increase by some 10%) in the 20-40 cm depth layer (Figure ~~6~~5). Note that, in general, resistivity changes of the type here observed cannot be uniquely associated to soil moisture content changes, as pore water conductivity may play a key role (e.g. Boaga et al., 2013; Ursino et al., 2014). However, in the particular case at hand, care was taken to analyze the electrical conductivity of both the water used for irrigation and the pore water, purposely extracted at about 50 cm depth. Both waters showed an electrical conductivity value in the range of 1300 µS/cm (thus fairly high, fact that explains the overall small soil resistivity observed at the site). Therefore in this particular case we can exclude pore water conductivity effects in the observed dynamics of the system. Once again it must be stressed that this is rather the exception than the rule.

A laboratory-based method was adopted for obtaining “unaltered” soil pore water through a column displacement technique (Knight et al., 1998). In particular, Rhizon soil moisture samplers (Cabrera, 1998) were used; they represent one of the latest developments in terms of tension samplers, where it is necessary to apply a suction to withdraw pore water with a vacuum tube (Tye et al., 2003). .

The qualitative evidence above is, however, not very surprising and not particularly informative: the root activity dries the soil, this is not a discovery. Things become more interesting if we can translate the ERT data into quantitative estimates of soil moisture content, and if we can use these data to calibrate hydrological models of the root zone.

To this end, we tested Bulgherano soil samples in the laboratory to obtain a suitable constitutive relationship linking moisture content and resistivity, given the know pore water conductivity that was reproduced for the water used in the laboratory. All measurements were conducted using cylindrical Plexiglas cells equipped with a four-electrode configuration designed to allow for sample saturation and de-saturation with no sample disturbance, using an air injection apparatus at one end and a ceramic plate at the opposite end. samples. The air entry pressure of the ceramic is 1 bar, thus during all the experiments the plate remained under full water saturation, while allowing water outflow during de-saturation. At each de-saturation step, the electrical conductivity of the sample was measured under temperature controlled conditions using a ZEL-SIP04 impedance meter (Zimmermann et al. 2008). A completed description of the setup is given by Cassiani et al. (2009b).

Figure ~~7~~ 6 shows two example experimental results on samples from two different depths. Note how in a wide range of soil moisture content (roughly from 5% to saturation) the two curves in Figure ~~7~~ 6 lie practically on top of each other. The same applies for all tested samples. Note also that, even though some samples show the effect of the conductivity of the solid phase (through its clay fraction) at small saturation (see sample from 0.4 m in Figure ~~7~~6) still the effect is small as it appears only at soil moisture smaller than 3-4%. Therefore we deemed unnecessary to resort to constitutive laws that represent this solid phase effect, such as Waxman and Smits (1968) that has been used for similar purposes elsewhere (e.g. Cassiani et al., 2012) and we adopted a simpler Archie's (1942) formulation. Consequently we translated resistivity into moisture content using the following relationship calibrated on the laboratory data, using a water having the above mentioned electrical conductivity:

$$\theta = \frac{4.703}{\rho^{1.12}} \tag{1}$$

where θ is volumetric soil moisture content (dimensionless) and ρ is electrical resistivity (in Ohm m). The relationship (1) allows a direct translation of the 3D resistivity distribution to a corresponding distribution of volumetric soil moisture content. However, it has long been established that inverted geophysical data may bring with them enough distortion of the true physical parameter field (Day-Lewis et al., 2005) as to induce violations of elementary physical principles, such as mass balance during tracer test monitoring experiments (e.g. Singha and Gorelick, 2005). This may cause substantial problems, particular when the use of data is expected to shift from a qualitative interpretation to a quantitative use in terms of data assimilation into hydrological models. For this reason, coupled versus uncoupled approaches have been proposed and discussed (Hinnell et al., 2010) even though their superiority seems to depend on the specific problem, as the information content of data even in a tradition, inverted approach may be sufficient

(Camporese et al., 2011, 2014). Indeed, the geometry we are considering here is very effective to reconstruct the mass balance of irrigated water, as this comes as a quasi-one dimensional infiltration front from the top, where in addition electrodes are located. The geometry is similar to the one used, e.g., Koestel et al. (2008) where mass balance was verified by comparison against very detailed TDR data collected in a lysimeter. In spite of these considerations, we decided to still limit ourselves to analyzing the data variation principally as a function of depth, lumping the data horizontally by averaging estimated moisture content along two-dimensional horizontal planes. Note that the dataset may lend itself to more complex analyses such as the one proposed by Manoli et al. (2014), especially if used in the context of a formal Data Assimilation, but we felt that one such an endeavor would exceed the scope of the current paper and deserves an ad-hoc space. Note also that the ERT field evidence both in terms of background (Figure ~~5~~4) and time-lapse evolution (Figure ~~6~~5) of moisture content confirm the hypothesis that, within the control volume, the distribution of water in the soil is largely one-dimensional as a function of depth.

The data, once condensed in this manner, lend themselves more easily to a comparison with the results of infiltration modeling. We implemented a one-dimensional finite element model based on a Richards' equation solver (*Femwater* – details of this classical model are given by Lin et al., 1997), simulating the central square meter of the ERT monitored control volume, down to a total depth of 2 meters (much below the depth of the ERT boreholes), where we assumed that the water table is located (Dirichlet boundary condition). We applied at the top of the soil column a Neumann boundary condition consistent with the flux coming from irrigation that pertains the control volume (basically, the water coming from a single dripper). As Femwater is a 3D simulator, the soil column is also bounded laterally by no-flow conditions, with the exception of the top 40 cm where we applied laterally a Neumann condition simulating the root water uptake (see below for details).

We ~~therefore~~ considered only the central part of the ERT-controlled volume (1 m x 1 m) thus excluding the regions too close to the boreholes that, even though benefitting from the best ERT sensitivity, might have been altered from a hydraulic viewpoint by the drilling and installing operations. Correspondingly we averaged horizontally the ERT data only in this central region.

A very fine vertical discretization (0.01 m) and time stepping (0.01 h) ensures solution stability. The porous medium is homogeneous along the column and parameterized according to the Van Genuchten (1980) model. The relevant parameters had been derived independently from laboratory and field measurements, the latter particularly relevant for the definition of a reliable in situ saturated hydraulic conductivity estimate. The parameters used for the simulations are: residual moisture content θ_r = 0., porosity θ_s=0.54, α = 0.12 1/m, n = 1.6, saturated hydraulic conductivity K_s = 0.002 m/h. We acknowledge that a more complete sensitivity analysis concerning the impact of the individual parameters would be beneficial, but this should be performed in a complete Monte Carlo manner in order to exclude identification trade-offs between the Van Genuchten parameters, the depth of the water table (known with some uncertainty) and the fluxes from irrigation, precipitation and evapotranspiration. However we feel that this endeavour shall be conducted also with regard to the effective 3D spatial distribution of active roots, and is currently the subject of ongoing research.

The remaining elements of the predictive modelling exercise are initial and boundary conditions. As we focused primarily our attention on reproducing the state of the system at background conditions, we set the start of the simulation at the beginning of the year (1/1/2013), and we assumed for that time a condition drained to equilibrium. Given the van Genuchten parameters we used and the depth of the water table, this corresponds to a fairly wet initial condition. We verified a posteriori that moving the initial time back of one or more years did not alter the predicted results at the date of interest (October 3, 2013). The dynamics during the year are sufficient to bring the system to the real, much drier condition in October. The forcing conditions on the system are all known: (a) irrigation is recorded, and only one dripper pertains to the considered square meter; (b) precipitation is measured; (c) sap flow is measured. Direct evaporation from the square meter of soil around the stem is neglected, considering the dense canopy cover and the consequent limited radiation received. Only one degree of freedom is left to be calibrated, i.e. the volume from which the roots uptake water. Thickness of the active root zone was estimated from the time-lapse observations (Figure ~~6~~5), and fixed to the top 0.4 cm after checking that limiting the root uptake to the 0.2 m to 0.4 m zone would produce results inconsistent with observations in the top 0.2 m. Therefore only the surface area of the root uptake zone remains to be estimated. We used the predictive model as a tool to identify the extent of this zone, that is of critical interest also for irrigation purposes.

Figure ~~8~~ 7 shows the results of the calibration exercise. It is apparent that the total areal extent of the root uptake zone has a dramatic impact on the predicted moisture content profiles, as it scales the amount of water subtracted from the monitored square meter considered in the calibration. Even relatively small changes (+/-15%) of the root uptake area produce very different soil moisture profiles. The value that allows a good match of the observed profile is 1.75 m^2, while for areas equal to 1.5 m^2 and 2 m^2 the match is already unsatisfactory, leading respectively to underestimation and overestimation of the moisture content in the profile.

Another important fact that is apparent from Figure ~~8~~ 7 is that the estimated soil moisture in the shallow zone (roughly down to 0.4 m) is very small as an effect of root water uptake. However this dry zone must have a limited areal extent (1.75 m^2, corresponding to a radius of about 0.75 m from the stem of the tree). Indeed this is indirectly confirmed by the soil moisture evolution measured by TDR. Figure ~~9~~ 8 shows the TDR data from three probes located about 1.5 m from the monitored tree (thus outside our estimated root uptake zone). The signal coming from the irrigation experiment of October 2, 2013 is very apparent with an increase in moisture content of all three probes, located at different depths. Note that before this experiment the system had been left without irrigation for about two weeks. The corresponding effect on the TDR data is apparent: all three probes show a decline of moisture content during the day, with pauses overnight. The decline is more pronounced in the 0.35 m TDR probe, that lies at a depth we estimated to be nearly at the bottom of the RWU zone, and less pronounced above (0.2 m) and below (0.45 m). Note also that the TDR probes are close to another dripper, lying outside of the ERT controlled volume (the drippers are spaced 1 m along the orange trees line, with the trees about 4 m from each other) thus they reflect directly the infiltration from that dripper. ~~.~~However, at all three depths the moisture content is much higher than measured in the ERT-controlled block closer to the tree. This can be explained with the fact that in that region the root uptake is minimal or totally absent, while the decline of moisture content in time may well be an effect of water being drawn to the root zone by lateral movement induced by the very strong capillary forces exerted by the dry fine grained soil in the active root zone closer to the tree. In order to clarify the impact of these results on our understanding of the system, we show the location of the trees, of the TDR probes and of the drippers in Figure 9, where we also sketch the best estimate for the areal extent of the RWU zone. This Figure clearly highlights how critical the information provided by ERT actually is. The scale at which RWU takes place is smaller (meter scale) than expected and often assumed when it comes to designing and implementing a field monitoring system. This has dramatic consequences in terms of how reliable conclusions can be drawn if such a small scale processes are neglected. Consider, e.g., what type of conclusions could be drawn on the basis of TDR data alone (Figure 8) in light of the field situation as depicted in Figure 9. The single, most important message that shall be conveyed by this paper is a warning to be particularly attentive to small scale processes in soil-plant-atmosphere interactions, even in regular agricultural landscapes.

5. CONCLUSIONS

Near surface geophysics is strongly affected by both static and dynamic soil/subsoil characteristics. This fact, if properly recognized, is potentially full of information on the soil/subsoil structure and behaviour. The information is maximized if geophysical data are collected in time-lapse mode. In the case of interactions with vegetation, its role should be properly modelled, and such models can be constrained by means (also) of geophysical data. This case study demonstrates that 3D ERT is capable of characterizing the pathways of water distribution, and provides spatial information on root zone suction regions. The integration of modelling and data has proven, once again, a key component of this type of hydro-geophysical studies, allowing us to draw quantitative results of practical interest. In this case we had available a wealth of quantitative information about transpiration and soil moisture content that allowed the definition of the volume of soil affected by the RWU activity. This has obvious consequences for the possible improvement of irrigation strategies, as it is apparent how the monitored orange tree essentially drives water from 1 to 2 drippers out of the 4 total that should pertain to its area in the plantation. This means that it is very likely that half of the irrigated water is indeed lost to deeper layers and brings no contribution to the plants. More advanced uses of this type of data are now considered, especially linking soil moisture distribution with plant physiological response and active root distribution in the soil. In the long run studies of this type may give a fundamental contribution to our understanding of soil-plant-atmosphere interactions also in view of facing challenges coming from climatic changes.

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Acquisition #	Starting time	Ending time	Irrigation schedule	Date
0 (background)	10:40	11:00	11:30 to 16:30 4 l/h from each dripper	October 2, 2013
1	12:00	12:20		
2	13:00	13:20		
3	14:15	14:35		
4	15:00	15:20		
5	16:00	16:20		
6	17:00	17:20		
7	10:15	10:35	7:00 to 12:00 4 l/h from each dripper	October 3, 2013
8	11:05	11:25		
9	12:00	12:20		
10	13:00	13:20		
11	14:00	14:20		
12	15:00	15:20		
13	15:45	16:05		

Table 1: times of acquisitions and irrigation schedule

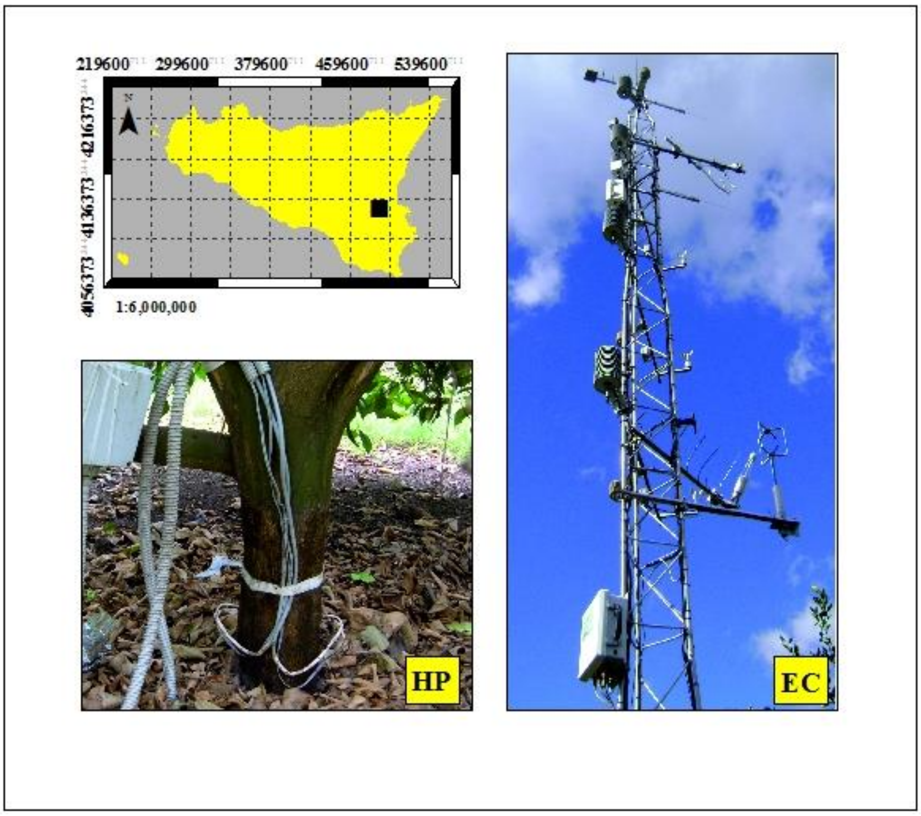
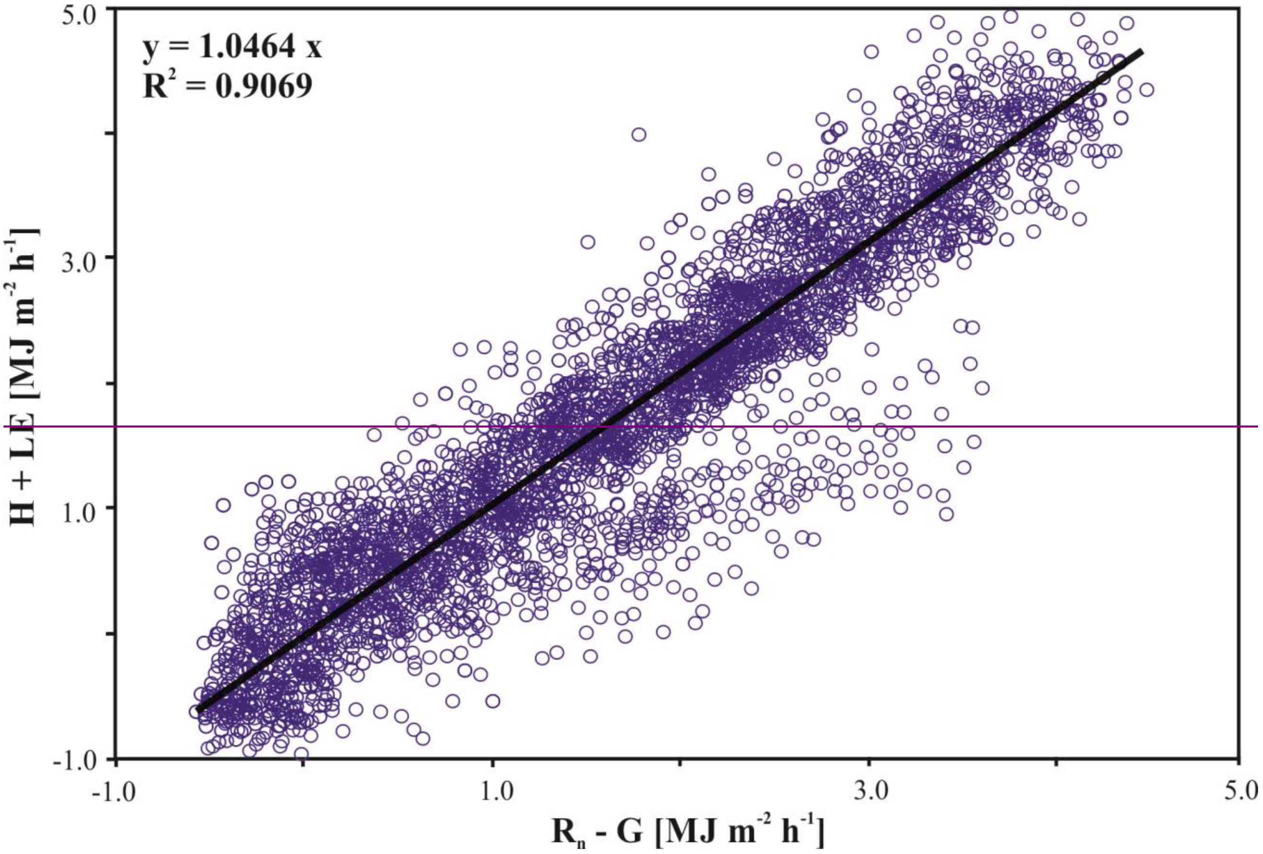


Figure 1: Bulgherano experimental site: the Eddy Covariance (EC) tower and a Heat Pulse (HP) Sap Flow installation on an orange tree.



~~**Figure 2:** Energy Balance closure at the Bulgherano experimental site.~~

Figure 2~~3~~: 3D ERT apparatus installed around one orange tree. The system is composed of four micro-boreholes carrying 12 electrodes each (see inset) and 24 surface electrodes – see text and Figure ~~4~~ 3 for geometry details.

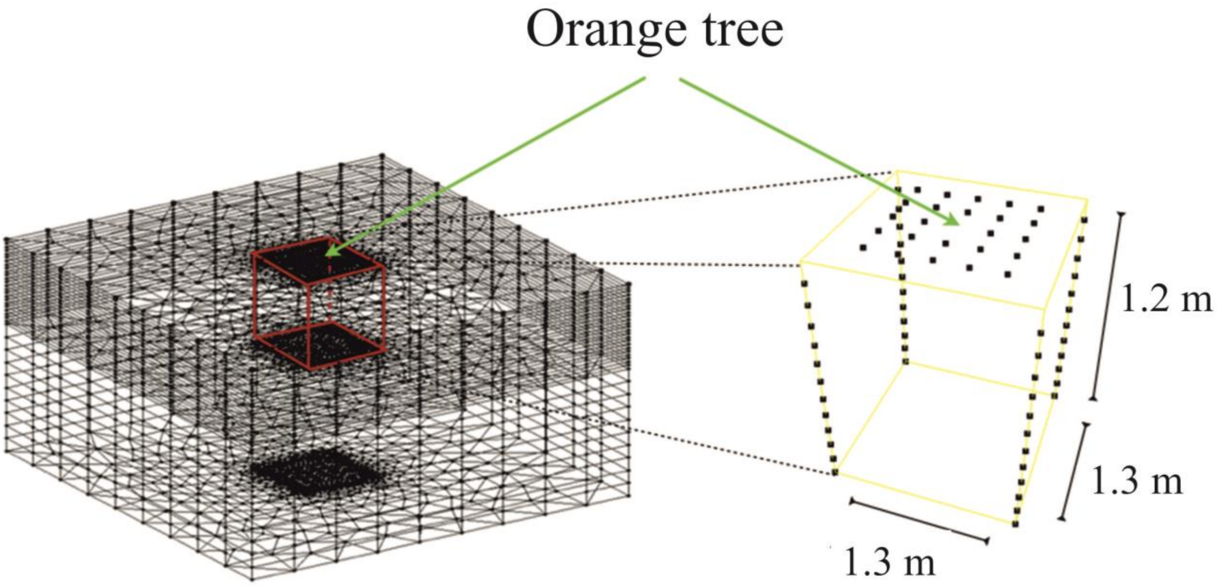


Figure ~~4~~3: Electrode geometry around the orange tree and 3D mesh used for ERT inversion.

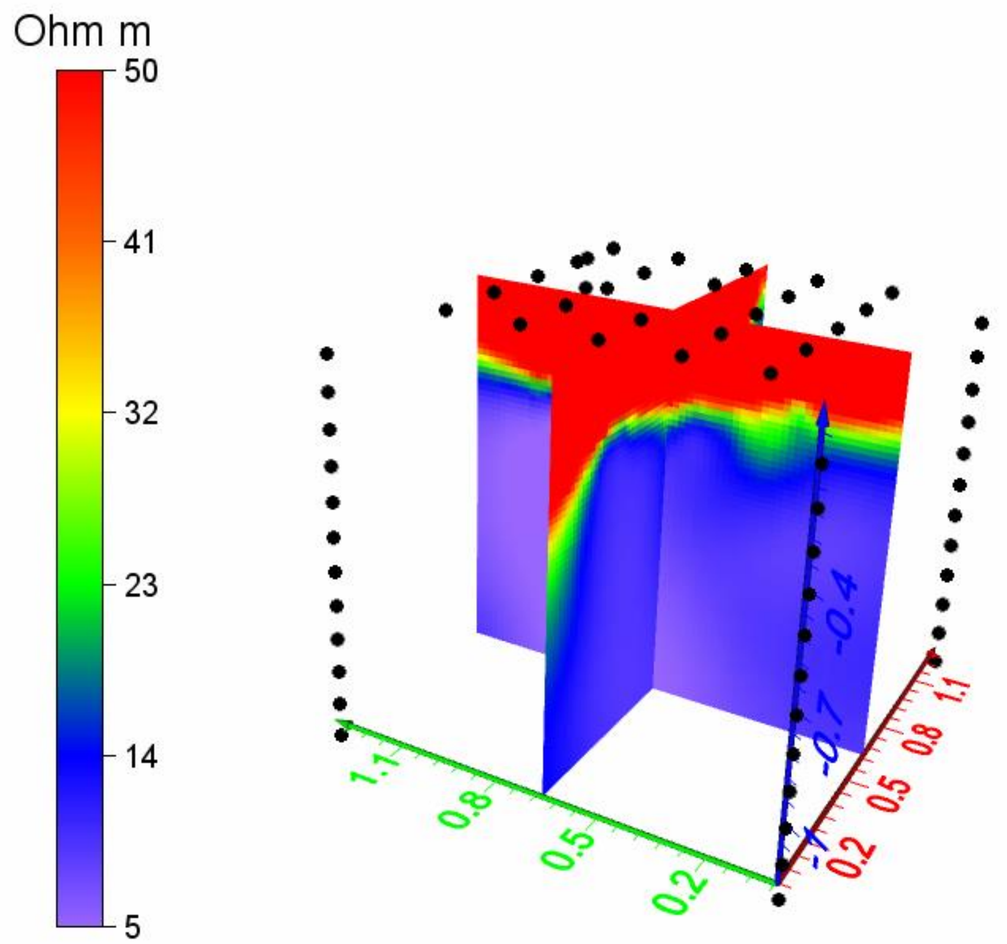


Figure 4~~5~~: cross-sections of the ERT cube corresponding to the background acquisition of October 2, 2013, 11:00 a.m. Note the very strong difference in electrical resistivity between the top 40 cm (above 50 Ohm) and the rest of the domain. The resistivity distribution is essentially one-dimensional with depth, with very limited horizontal variations.

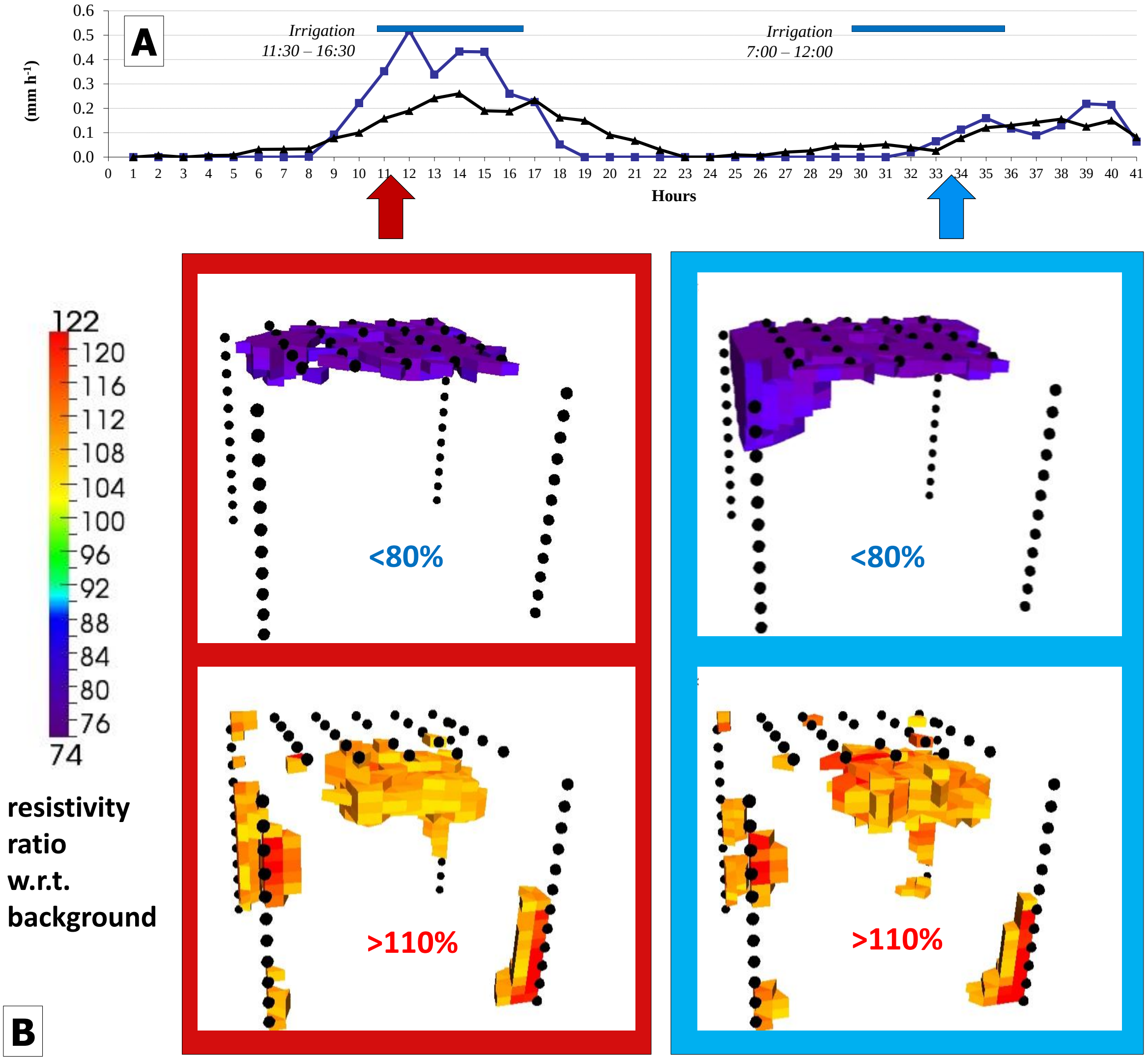


Figure 5~~6~~: (A) time series of sap flow (black line) and EC-derived total evapotranspiration (blue lines), both normalized in mm assuming an area of 20 m^2 pertaining to the orange tree monitored with ERT. Time is given in hours from midnight of October 2. The two irrigation periods are shown by the blue bars. (B) 3D ERT images of resistivity change with respect to background at two~~four~~ selected time instants shown by the arrows in (A); the volumes corresponding to increase and decrease of resistivity above and below certain thresholds (80% and 110%) are shown in separate panels, for clarity.

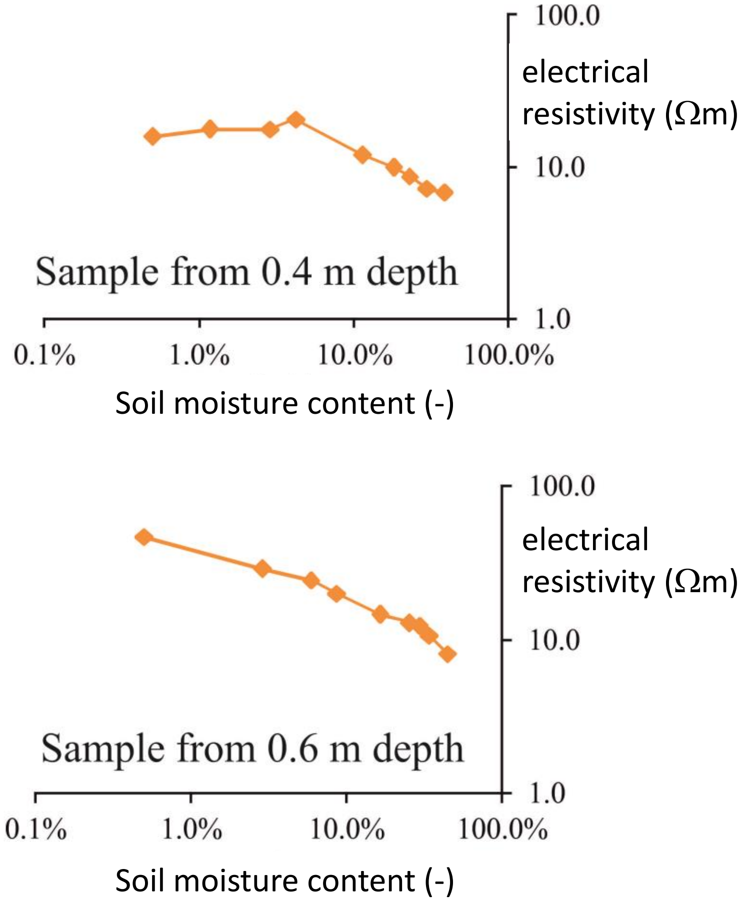


Figure 6~~7~~: experimental relationships between resistivity and moisture content determined in the lab on samples taken at two different depths at the Bulgherano site, using water having the same electrical conductivity measured in the pore water in situ.

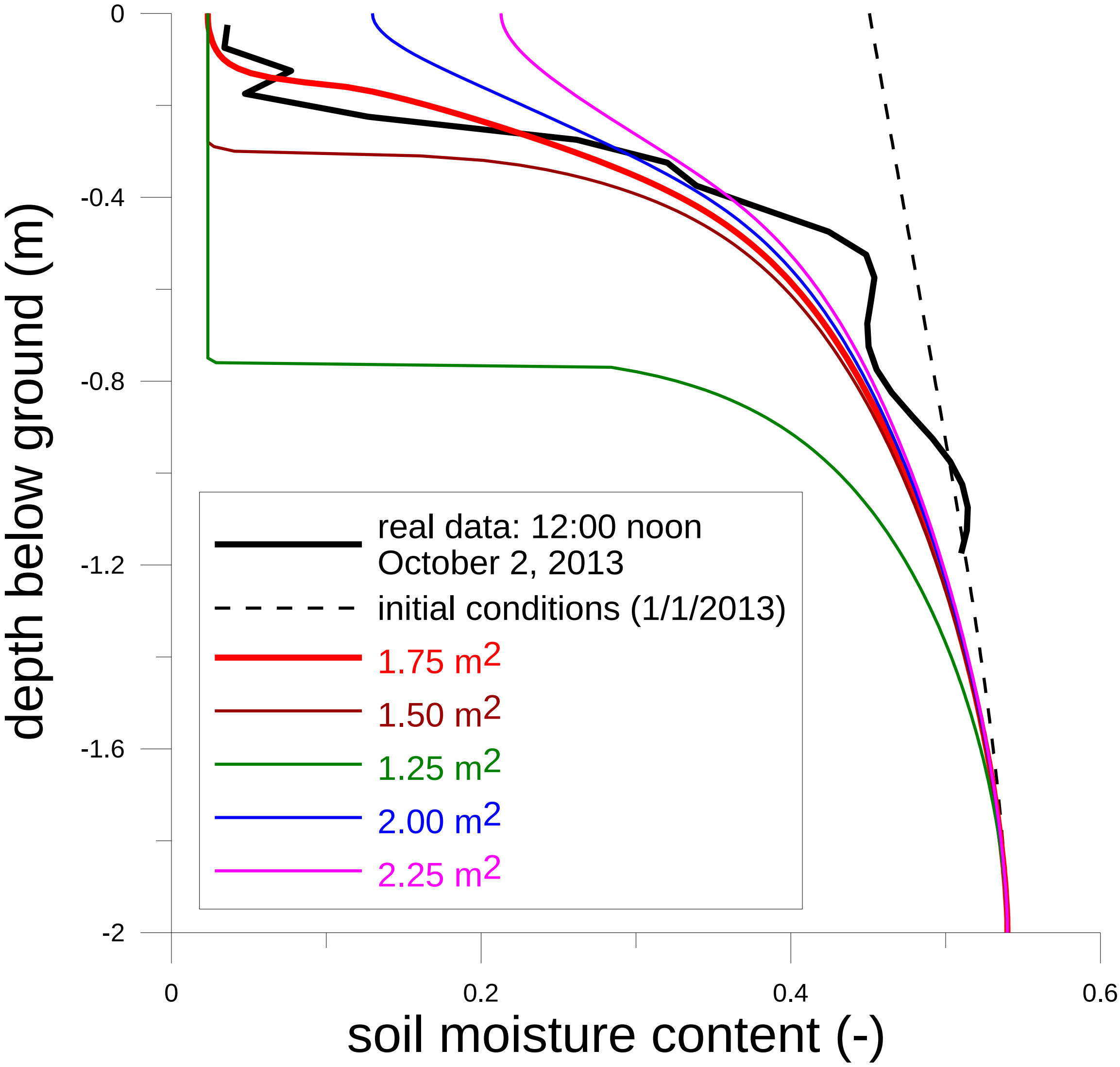


Figure 7~~8~~: results of 1D Richards' equation simulations of the entire year 2013 till October 3, 11:00 a.m., i.e. in correspondence of the background ERT acquisition (the thick black line represents the resulting estimated moisture content profile obtained from averaging horizontally the central square meter of the ERT control volume). The different simulated curves correspond to different assumed areas of root water uptake, and show how 1.75 m2 is the area that allows to match the observed real profile with good accuracy. Note also the high sensitivity of the results to the estimated root uptake area.

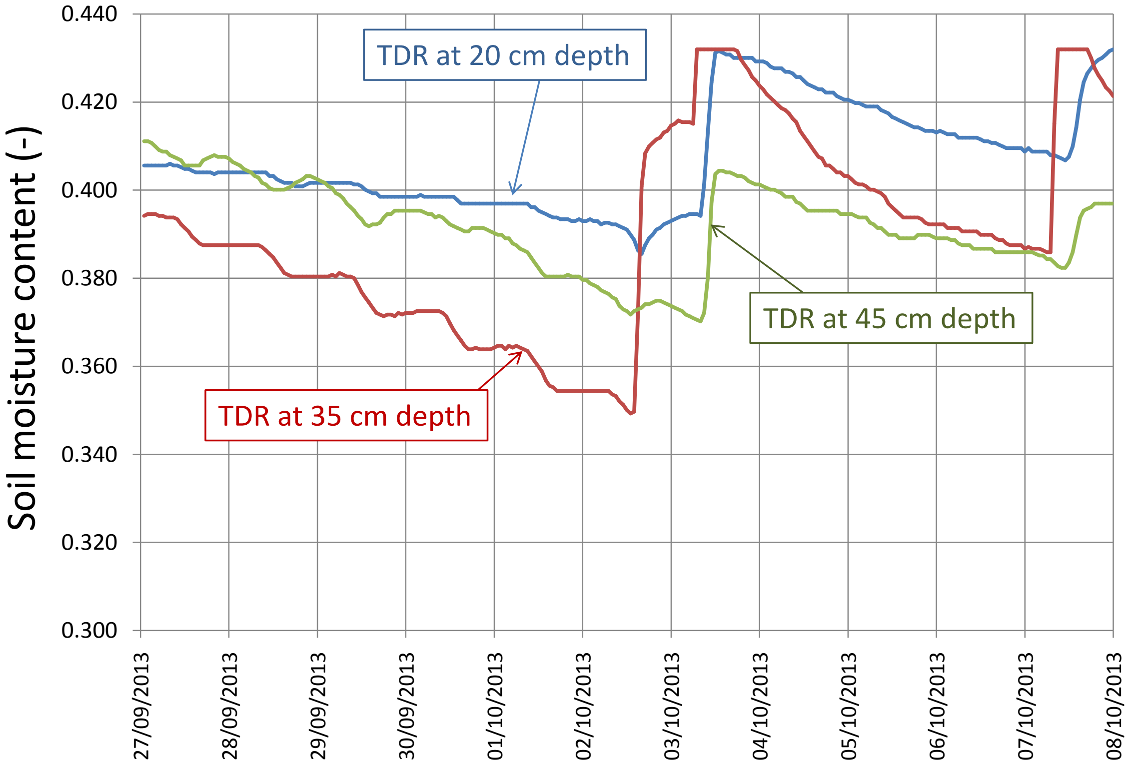


Figure 8~~9~~: moisture content time series from three TDR probes located about 1.5 m from the ERT-monitored tree. The signal coming from the irrigation experiment of October 2, 2013 is very clear. Before this experiment the system had been left without irrigation for about two weeks.

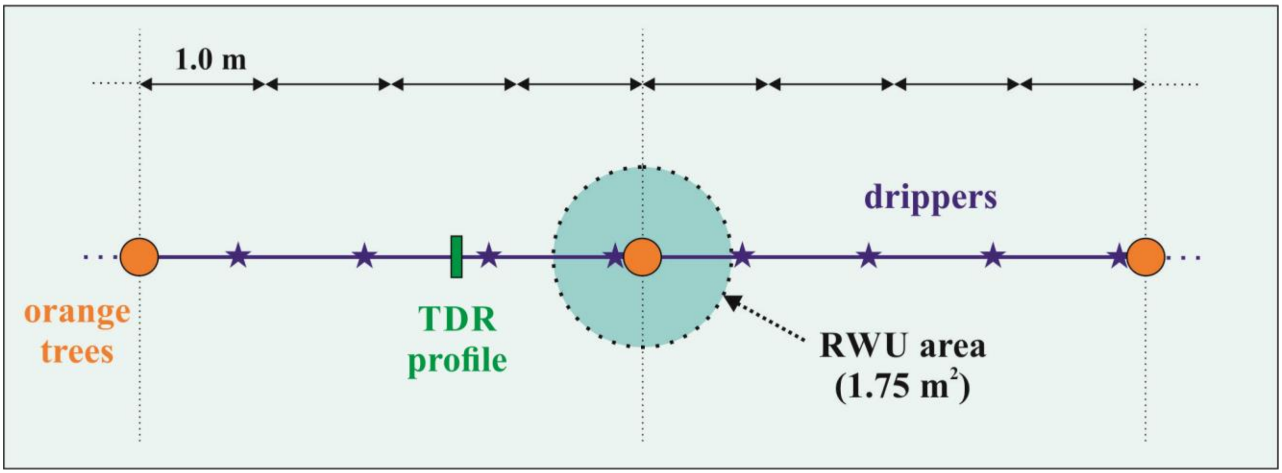


Figure 9: scheme of the experimental field with the location of the main sensors. The radius of the root water uptake zone, assumed to be circular, is equal to about 0.75 m.