Science of the Total Environment 543 (2016) 851–861

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Soil–plant interaction monitoring: Small scale example of an apple orchard in Trentino, North-Eastern Italy

Giorgio Cassiani [a,*], Jacopo Boaga [a], Matteo Rossi [a], Mario Putti [b], Giuseppe Fadda [b], Bruno Majone [c], Alberto Bellin [c]

[a] Dipartimento di Geoscienze, Università di Padova, Italy
[b] Dipartimento di Matematica, Università di Padova, Italy
[c] Dipartimento di Ingegneria Civile e Ambientale, Università di Trento, Italy

## HIGHLIGHTS

- A novel noninvasive geoelectrical system is proposed for root water uptake monitoring.
- The approach is applied to an apple orchard in Northern Italy.
- Results indicate the need to consider also pore water electrical conductivit.

## ARTICLE INFO

*Article history:*
Received 10 January 2015
Received in revised form 11 March 2015
Accepted 26 March 2015
Available online 2 April 2015

*Keywords:*
Hydrogeophysics
Irrigation experiments
Vadose zone
Root activity

## ABSTRACT

Accurate monitoring and modeling of soil–plant systems are a key unresolved issue that currently limits the development of a comprehensive view of the interactions between soil and atmosphere, with a number of practical consequences including the difficulties in predicting climatic change patterns. This paper presents a case study where time-lapse minimal-invasive 3D micro-electrical tomography (ERT) is used to monitor rhizosphere eco-hydrological processes in an apple orchard in the Trentino region, Northern Italy. In particular we aimed at gaining a better understanding of the soil–vegetation water exchanges in the shallow critical zone, as part of a coordinated effort towards predicting climate-induced changes on the hydrology of Mediterranean basins (EU FP7 CLIMB project). The adopted strategy relied upon the installation of a 3D electrical tomography apparatus consisting of four mini-boreholes carrying 12 electrodes each plus 24 mini-electrodes on the ground surface, arranged in order to image roughly a cubic meter of soil surrounding a single apple tree. The monitoring program was initially tested with repeated measurements over about one year. Subsequently, we performed three controlled irrigation tests under different conditions, in order to evaluate the water redistribution under variable root activities and climatic conditions. Laboratory calibration on soil samples allowed us to translate electrical resistivity variations into moisture content changes, supported also by in-situ TDR measurements. Richards equation modeling was used also to explain the monitoring evidence. The results clearly identified the effect of root water uptake and the corresponding subsoil region where active roots are present, but also marked the need to consider the effects of different water salinity in the water infiltration process. We also gained significant insight about the need to measure quantitatively the plant evapotranspiration in order to close the water balance and separate soil structure effects (primarily, hydraulic conductivity) from water dynamics induced by living plants.



## 1. Introduction

In recent years a growing attention has been attracted by the importance of understanding and characterizing the manifold processes that take place in the so called Earth's "Critical Zone" (ECZ) as defined by the U.S. National Research Council (2001). The ECZ represents the thin veneer of our planet from the top of the tree canopy to the bottom of drinking water aquifers. Being at the interface between the planet and its atmosphere, the ECZ is a complex natural reactor, where inputs of solar energy, atmospheric deposition and gas fluxes interact with the biota and rock mass to maintain soil, nourish ecosystems and accumulate and exchange water (Anderson et al., 2004; Brantley et al., 2006). This diversity of interactions presents an enormous scientific challenge to understanding the linkages and chain of impacts. In particular, within the ECZ, the interactions between soil, plants and atmosphere (SPA)

* Corresponding author.

http://dx.doi.org/10.1016/j.scitotenv.2015.03.113

play a fundamental role in the exchanges of mass (especially water and $CO_2$) and energy, that in turn control a number of environmental processes of the highest general interest, including those affecting and mitigating climatic changes. Terrestrial vegetation modulates and sustains evapotranspiration (ET) and precipitation. ET has been termed “green water” flow (Falkenmark and Rockstro¨m, 2004). Root-zone soil moisture is the major stock of green water. Soil moisture affects biota directly, by controlling the availability of resources for organisms, and indirectly, by modifying abiotic processes that affect ecosystem dynamics. Green water stocks and flows are affected by biological processes, primarily mediated by plants, with multiple feedbacks from soil and atmosphere, thereby affecting surface energy and water-vapor fluxes, boundary layer dynamics, precipitation, and soil moisture regime (e.g., Bonan, 2002). On a larger scale, the response of terrestrial ecosystems to global change is often mediated or sustained by changes in soil moisture dynamics (Rodriguez-Iturbe and Porporato, 2005). Climate warming enhances ET, thereby accelerating the hydrologic cycle, and climate change research predicts changes in both the mean and the variance of hydrological drivers (Easterling et al., 2000). Also of great impact is the understanding of the relevant processes taking place in agricultural practice, in order to optimize irrigation and plant resilience in face of expected climatic changes and growing population demands (“more crop per drop”, Tilman et al., 2001; Howden et al., 2007).

In spite of the scientific challenges described above, the understanding of complex SPA interactions is still limited, particularly regarding the subsoil components, including root activities, and their changing states, mainly by the lack of spatially extensive and time intensive data. Common point-based methods do not allow the investigation of state variables' spatial distribution. Remote sensing techniques generally penetrate the subsoil only by a few centimeters and their view of the subsurface is hindered by the vegetation itself.

To fill this knowledge gap, innovative non-invasive and spatially extensive techniques are more and more often called into play (Jayawickreme et al., 2014). Ground-based, non-invasive (geophysical) techniques such as Electro-Magnetic methods, Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) have been increasingly applied at different scales to image static and dynamic characteristics of the subsoil, particularly for hydrological purposes (Vereecken et al., 2006; Binley et al., 2011). Recently, these techniques have also been used for dynamic hydro-biological characterization (e.g. Wiley et al., 2010). The use of non-invasive techniques, GPR and ERT in particular, can be considered state-of-the-art for the estimation of moisture content changes (Binley et al., 1996, 2002; Deiana et al., 2007). However, the application of these techniques to the very small scale and at the resolution needed for SPA interactions is not a trivial technical task, so that the use of these techniques for investigation at the root-zone scale is still in its infancy. In addition, the interpretation of the results in terms of soil dynamics has non-trivial intricacies, involving moisture content, pore water salinity and temperature [e.g., Cassiani et al., 2012; Ursino et al., 2014].

In the framework of plants/subsoil interactions, ERT has been downscaled to image the root zone geometry (Amato et al., 2008; Werban et al., 2008; Petersen and al Hagrey, 2009; Nijland et al., 2010; al Hagrey and Petersen, 2011; Robinson et al., 2012). Similarly, GPR has been used to try and identify particularly the root structure in the shallow subsoil (Butnor et al., 2001; Leucci, 2010; Bassuk et al., 2011). However, neither GPR nor ERT has been proven to be fully capable of identifying the details of the small-scale root system structure, even though some success has been reported in specific cases (Rossi et al., 2011; Wu et al., 2014). This is indeed not surprising, as geophysical techniques can only sense the spatial patterns or the temporal changes in the physical parameters they measure, so contrasts in physical properties between roots and the surrounding soil are needed to detect roots per se. This lucky situation rarely takes place, at least using electrical or electromagnetic methods that are by far the most used techniques for this purpose. Therefore the identification of root geometry and the quantification of root mass, that could have important consequences for carbon sequestration assessments, remains largely an unresolved issue.

A different approach is to try and quantify root water uptake (RWU) from changes in soil moisture content and consequently from changes in geophysical quantities that depend on that, such as electrical resistivity and dielectric constant. From this information one can draw conclusions about mass and energy transfers between soil and atmosphere as mediated by plants. Examples of this approach date back at least a decade, with a recent growing interest (Michot et al., 2003; Jayawickreme et al., 2008, 2010; Beff et al., 2013; Macleod et al., 2013; Boaga et al., 2014; Cassiani et al., 2015; Shanahan et al., 2015). Generally speaking, such an approach is a particular case of more general hydro-geophysical methods and a full exploitation of the data information content can be expected if data and modeling are used jointly, for instance using advanced Data Assimilation techniques (see e.g. Hinnell et al., 2010; Camporese et al., 2011, in press; Manoli et al., 2015).

The EU FP7 project CLIMB (Climate Induced Changes on the Hydrology of Mediterranean Basins — Ludwig et al., 2010) had among its goals the reduction of uncertainty in the prediction of climate change impacts on the hydrology of Mediterranean basins. One of the study areas was the Noce river catchment in Trentino, North-Eastern Italy. The lower river catchment (Val di Non) is a region of intensive apple production. Therefore knowledge of the apple tree orchards' water dynamics is key to the understanding of the local hydrology, especially as apple trees require a very intense irrigation during summer time. Therefore we focused our attention on the root/vadose zone description of the apple tree orchards. This area of investigation posed new, demanding, interdisciplinary challenges among which is the collection and interpretation of spatially extensive and time intensive non-invasive data that can greatly contribute towards the understanding of the soil–plant–atmosphere interaction at an unprecedented scale and resolution.

In this paper we present the results of the very small-scale ERT acquisitions around a single apple tree in the Val di Non. We conducted monitoring of both long term natural changes and controlled irrigation experiments, in order to assess value, strengths and limitations of the non-invasive techniques for root/vadose zone monitoring. The main goals of this study were:

(a) to study the small scale dynamics of moisture content in an apple orchard where irrigation is the main source of water during the growing season;
(b) to test and validate the capabilities of small-scale ERT for the monitoring of eco-hydrological processes at the small scale, where processes of primary interest for soil–plant–atmosphere interactions take place;
(c) to assess the value of unsaturated flow modeling in supporting and validating the conclusions drawn on the basis of time-lapse hydro-geophysical monitoring.

## 2. The test site

The experimental site is an apple orchard located at Maso Maiano, near Cles, in ‘Val di Non’ valley, Trentino (Fig.1). ‘Val di Non’ is a mountain region widely known for apple production. The orchard has an area of roughly 5000 $m^2$ with an elevation of about 640 m.a.s.l. There are about 1200 apple trees (cultivar Golden Delicious) planted in 2004 along North–south rows spaced about 3.5 m. Plants are placed at about 1 m from each other along each row and the canopy height is about 2.5 m. The apple trees have an average stem diameter of approximately 0.04 m. In the field the soil surface is managed with a grass cover. The site is located on a moraine versant of an ancient Wurmian glacier valley and the soil is a heterogeneous glacial deposit, with stones