Introduction. We are fronting an increasing global demand of optimization in terms of land use and water management, both for civil exploitation and agriculture. This means a growing demanding in quality and quantity calls for sustainable management of water catchments and better understanding of water and solute movement in the critical vadose zone. Non invasive geophysical techniques can play a key role in the hydrological investigation of the near surface, as they provide spatially extensive imaging that complement the more traditional hydrological point measurements (e.g. Vereecken et al., 2006). Between geophysical techniques, time-lapse Electrical Resistivity Tomography (ERT) was recently adopted in several studies to estimate, albeit indirectly, changes in moisture content (e.g. Binley et al. 2002, Strobbia and Cassiani, 2007) and solute concentration (Cassiani et al., 2006). In the framework of plants/subsoil interactions ERT techniques were recently downscaled to image the root zone geometry (Jayawickreme et al., 2008; Muller et al., 2003; Werban et al., 2008; al Hagrey and Petersen, 2011; Jarvaux et al., 2008). These applications pose new interdisciplinary high demanding challenges from ecohydrology to geocohydrology (Eagleson, 2002). In this framework we are applying hydrogeophysical methodologies to several sites of different climatic zones in terms of upper soil hydrology, downscaling non invasive geophysical techniques to the upper subsoil biosphere interactions.

The aim of this work was to apply ERT techniques to the monitoring of plant root zone for 2 field cases. For this specific purpose it is necessary a 3D ERT apparatus with very detailed resolution capabilities and, due to the small target, extremely attention to be non invasive. In order to get a 3D resistivity imaging under a plant, we need small inter-electrodes spacing both in depth buried electrodes and surface ones. We need also the lowest possible resistance contact with soil and the minimum site disturbance together with reasonable efficiency in time to perform time-lapse measurements. For all these reasons we designed 1 inch PVC boreholes totally internal wired, equipped with 12 round steel electrodes each with 0.1m spacing.
We present on the results of experiments of 3D and 2D Micro-ERT, supported by Time Domain Reflectometer (TDR) measurements and tensiometers measurements in a very well monitored fruit garden of Val di Non, Trentino Region and for the Venice lagoon salt marsh environment (Italy). In the specific we performed 3 controlled irrigation tests for the apple tree and 1 field experiment in the Venice lagoon during marsh flooding. Very different seasonal and environmental conditions are highlighted with interesting behaviors. In order to quantify soil moisture content in the first case study, we performed laboratory analysis on earth samples to evaluate the electrical response at different saturation steps and to calibrate petro-physical relationships. This allows transforming geophysical quantities into hydrological quantities, which represents a key point to clearly understand the groundwater dynamics and soil-plant interactions.

**Test sites.** Test site 1 is located in Cles (650 m amsl), in the Val di Non valley of Trentino Region, North Italy. We installed our micro ERT 72 channels (48 buried electrodes + 24 surface electrodes) and 2 TDR antennas around a single tree in an apple culture, already monitored in the framework of the FP7 CLIMB project, with controlled irrigation system and monitored weather-stations. The site is located on a moraine versant of an ancient Wurmian glacier valley and presents an heterogeneous glacial deposit (presence of blocks and pebbles in a sandy-silty matrix). We conducted monitoring of both long term natural changes and controlled irrigation experiments around a single apple tree, in order to assess value, strengths and limitations of the non invasive techniques for root/vadose zone monitoring.

Test site 2 is located in the northern part of the Venice Lagoon (Italy), in a periodically flooded salt marsh. In this case the ERT apparatus had 24 buried electrodes plus 24 surface...
electrodes. 3 tensiometers with log recorder were installed at 20, 30 and 40 cm depth in the subsoil.

Methods. Our 3D micro ERT configuration consists of 24 or 48 electrodes buried in depth, installed on boreholes, plus 24 steel electrodes on the surface. Electrodes are round steel electrodes spaced 0.1 m, with all wire connection sited inside the PVC casing. This allows their installation by percussion avoiding invasive pre-drill with a very efficient contact resistance between electrodes and soil.

For all the measurements we adopted a dipole-dipole skip-zero acquisition. For the inversion process we adopted a 3D mesh with detailed triangular prisms elements of 0.025 m side for the root zone box, while larger mesh cells were used for the background. All reciprocal measures, that show the statistical operator RSD (Relative Standard Deviation) exceeding the 5%, were removed from the dataset. The reciprocal procedure leads to different datasets, so to have comparable results the inversions are performed only on the same quadripoles that are present in all datasets. For the inversion we adopted the codes R3T (Binley et al., 2011), a 3D current flows solution for finite element triangular prisms mesh.

In order to enhance the time-lapse monitoring we inverted the data as a ratio of electrical resistances at a specific time respect to the resistance values at the background measurement (in our case the time step before the irrigation):

$$R = \left( \frac{R_i}{R_0} \right) R_{\text{hom}}$$  \hspace{1cm} (1)

where $R_i$ is the electrical resistance at the $i$-th time-step, $R_0$ is the electrical resistance at the background measure and $R_{\text{hom}}$ is the electrical resistance for an homogenous space of 100 Ω·m. The inversion of resistance values can clearly enhances the variation of electrical resistivity during the time-lapse experiment. The results of the inversion is a map of the percentage variation of resistivity respect to the background values: values equal to 100 Ω·m show unchanged resistivity during time, while values less or more than 100 Ω·m show a decreasing or an increasing resistivity, respectively.

Results.

The Val di Non case studies. We performed 3 irrigation tests in 3 different seasonal conditions and with different type of irrigation. In August 2011 we performed a drip irrigation (2.4 lt/h) experiment under the dry conditions of the summer season. In May 2012 we performed a widespread irrigation experiment (198 lt/h) in a wet conditions during the highest spring dynamic growing season period of the plants, and in November 2012 we repeated the experiment in very wet condition. For the first experiment micro enhanced the conductive areas are restricted on the 2 drip irrigation points. The wet areas progressively expand during irrigation; after the end of the irrigation the shallow wet areas slowly start to dry (Fig. 1a). The second and third irrigation experiments were conducted in different climatic conditions, during the top of the growing season plant. The site soil this time was very wet due to huge amount of rain during the previous month. The hot sunny days of the experiment (26°), assured a large amount of evapotranspiration. We used an irrigation sprinkler system in order to obtain a more uniform and widespread irrigation as possible. We performed also Time Domain Reflectometer (TDR) measurements during and after the irrigation to estimate soil-water content ($\theta$).

Results (Fig. 1b) show how, at the depth where are expected the main suction zone linked to root plant activity (De Silva, 1999), there is a clear increasing of resistivity due to the root uptake. Extremely interesting is the shape of the drier zone since position of the root activity is not uniformly widespread on the horizontal plane, but it is confined in the area of the parallelepiped that is directly linked with the location of the drip irrigation system. Results of the 3d experiment (Fig. 1c) show also an higher resistivity zone at greater depth after 3 h from irrigation start. Since resistivity properties are not effect only of water saturation but also of salinity, we believe the observed phenomenon can be related to the replacement of the resident
water with the new low salinity irrigation water (piston effect). This very interesting aspect will be examined by the use of theoretical modeling.

Venice Lagoon case studies. Venice salt marsh location was chosen to test the capability of tidal plants to generate a persisting aerated layer in the subsoil when flooded, due to root uptake (Marani et al., 2006). We planned time lapse ERT measurements and tensiometers measurements before, during and after sea flooding of the marsh in a hot summer day (33°) of July 2012, with slow wind. This was expected to be the best conditions for salt marsh uptake process (potential evapotranspiration estimated to be approximately 8 mm/day, based on Penman-Monteith equation). Fig. 2 shows the inversion results at three time steps during the flooding of the marsh by seawater. Here we consider only the portion of subsoil between the instrumented boreholes, which presents the highest sensitivity. The three time steps are before the marsh is flooded (12:36 pm), when the marsh is flooded (2:40 pm), and after the marsh surface has been flooded and has started drying (3:11 pm) during ebb, the highest tidal level being of 0.34 m above MSL, at 1:52 pm.

These ERT ratio images clearly show the development of a zone of increased electrical resistivity near a depth of 30-40 cm below soil surface. Note that the tide starts flooding the marsh shortly after noon (that corresponds to the reference time instant) but is not visible per se in the ERT images, confirming that the high pore water salinity makes the system poorly sensitive to the modest change in water saturation due to water level rise. The area which is getting dryer during marsh flooding is the expected root zone for the typical wetlands vegetation (Sarcocornia fruticosa, Juncus, and Limonium nrbonense, etc.).

Tensiometers measurements, installed at 20, 30 and 40 cm depth confirmed the micro ERT results (Fig. 3). Surface tensiometers shows in fact a wetter condition when sea flooded the marsh but tensiometer installed at root depth (30-40 cm) show a surprising dryer condition during the flooding. ERT and tensiometers results are summarized in Fig. 3. The geophysical techniques were able enhance the dynamics interaction within marsh plants and first subsoil.

Discussion and Conclusion. We performed 3D and 2D micro-ERT measurements of root plant during controlled irrigation tests and natural flooding, in order to verify the potential of these non-invasive techniques to monitor the dynamic root zone activities.

The advanced 3D micro-ERT methodology exposed proved to be able to monitor suction zones, in good agreement to the expected root positions. In dryer conditions micro 3D-Ert image the penetrating water plumes injected, while in wetter high growing seasons of the plants micro 3D-ERT points out how certain subsoil zones are interested by quick drying conditions. These drying suction areas are in good agreement with the expected depth of the apple tree root activities. 3D micro ERT through indirect estimations enhanced the root zone
depth at which water content decay during the irrigation experiment, quantifying difference in water content zone by zone.

2D Time-lapse ERT in Venice lagoon enhanced how salt marsh plants are able to generate a persisting aerated layer in subsoil, even when flooded. In particular the large hyper-saline plants root uptake seems to be able to determine the persistence of an aerated layer, as previously observed (Marani et al., 2007, 2006; Ursino et al., 2004). It is authors’ opinion these analyses may help refine the understanding of the central importance of plant-soil interactions in coupling biological and geomorphological processes (via organic soil production and inorganic sediment trapping). The ERT methodology coupled with the tensiometer data can be used to quantify the dynamics of the soil water content, thus contributing to determine the state and evolutionary trends of tidal landforms forced by anthropogenic pressures and sea level rise.

In conclusion the non-invasive Micro-ERT techniques are promising tools for critical soil-plants interaction study, especially if they will support by advanced and accurate hydrological modelling. Suitable modelling techniques will be in fact necessary to exploit the information content of geophysical field data and answer critical questions about basic mechanisms, e.g. the soil moisture balance equations at the scale of the representative elementary volume (Bear, 1971; Richards, 1931).

Acknowledgements. We thanks Mario Putti, Giuseppe Fadda, Andrea D’Alpaos and Marco Marani for their invaluable supports for the modeling and interpretation of the results. We thank also Alberto Bellin and Bruno Majone for the Val di Non experiment. Funding for this work is acknowledged from the EU FP7 project CLIMB “Climate Induced Changes on the Hydrology of Mediterranean Basins” and from the Excellence Project “Transport phenomena in hydrological catchments: hydrological and geophysical experiments and modeling” funded by the CARIPARO Foundation.

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