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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

A non-invasive approach to monitor variability of soil water content with electromagnetic methods

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Abstract

An accurate and high-resolution description of the spatial variability of soil water content at the field scale and the distribution of water in the unsaturated zone requires a large number of measurements. Financial and time constraints limit the numbers of measurement locations; thus the standard approach for monitoring could lead to a large degree of uncertainty in spatial predictions.
We test in a parcel of bare soil an alternative approach based on ground-based geophysical techniques, by comparing the monitoring of the soil water content obtained from the Electrical Resisitivity Imaging and the Ground Penetrating Radar with the variability maps estimated from the interpolation of soil water contents measured in different locations with capacitance probes. The agreement is good and the integration of the techniques is promising.

Keywords: spatial variability; soil water content; electrical resistivity imaging; ground penetrating radar

1. Introduction

Many environmental and hydrological applications in the field of engineering, soil and agricultural sciences require knowledge about the variability of soil water content. Characterizing soil moisture variability in time and space is important to understand infiltration, redistribution of water after rain and

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irrigation event, evapotranspiration and fluid pollutant transport in the unsaturated zone. This is especially important for heterogeneous media which show even great variations both in vertical and horizontal directions [1, 2, 3, 4, 5]. An accurate and high-resolution description of the spatial variability of litho-textural properties and of soil water content at the field scale requires a large number of measurements. Financial and time constraints limit the numbers of measurement locations. Some authors suggest to use less accurate but cheaper sensor to increase the density of measurements [6, 7, 8]. Moreover recent studies [9, 10, 11, 8], specifically recommend to establish the site-specific calibration function since the accuracy of the sensors depends on field conditions. *Robinson et al., 2008* [12] provided a review for the standard methods to measure soil water content.

The most commonly used electromagnetic sensors are based on time domain reflectometry (TDR), frequency domain reflectometry (FDR) or capacitance techniques. The TDR-based sensors give the most accurate measurements but are of significantly higher cost than capacitance probes. The temporal variations of soil water content can be monitored by installing sensors in the field; nevertheless the installation of the sensors disturb the soil structure and the water flow [13].

For the limitations above mentioned the geophysical surface methods represent an interesting alternative way to monitor soil water content. These techniques have the advantages of being not invasive, so that the soil structure is not disturbed, able to rapidly obtain a large number of reproducible measurements and cost effective.

Huisman et al. [14] provided a comprehensive review of Ground Penetrating Radar (GPR) applications for soil moisture assessment. For this purpose, GPR ground-wave techniques are traditionally used [15,16,17,18,19]. Another theoretical approach is based on the use of volumetric dielectric mixing formulae [20]. Moreover, amongst the many petrophysical empirical relationships, the Topp correlation [21] is widely used to translate the permittivity retrieved by the GPR data inversions into soil moisture. In most cases, the aforementioned techniques require the use of destructive sampling, for calibration steps. Recent studies [22, 23, 24,25] are focused to provide efficient and self-consistent methods. *Benedetto, 2010* [24] used a Rayleigh scattering based method for direct evaluation of water content, without the need of a petrophysical relationship. At last, the Direct Current (DC) Electrical Resistivity Imaging (ERI) method represents a high-resolution tool to map both the distribution of water in the unsaturated zone and the soil properties [26]. In fact, as a first approximation, electrical resistivity of alluvial sediments and of soils depends upon the clay content, the pore water content and the electrical conductivity of pore water. In particular, for the application of ERI to the space-time variation of soil water content, it is necessary to separate the contribution of the lithological variation to the spatial distribution of the ground electrical resistivity.

The objective of this work is to evaluate the reliability of ERI and GPR in monitoring the variability of soil water content at the field scale and the usefulness of ERI to delineate soil heterogeneities. The physical properties measured with ERI and GPR techniques are analyzed comparing the results with the water contents measured with capacitance probes in some locations within a 20 m × 20 m parcel of bare soil.

Nomenclature

VWC	volumetric water content
VWC_{adj}	volumetric water content corrected with a in situ-calibration
GWC	gravimetric water content

2. Materials and methods

2.1. Experimental field and sampling design

The experimental site is a 20 m × 20 m parcel of bare sandy-loam soil located within a cropped field in Northern Italy (Landriano – PV), twenty kilometers south from Milan (Fig. 1). It is situated in a flat area at around 90 m a.s.l. characterized by a semi-humid climate with mean annual precipitation and temperature respectively of 880 mm and 12 °C [27]. Standard meteorological variables are measured by an agro-meteorological station installed at 200 m distance from the experimental field; the precipitation and mean temperature during the monitoring period are shown in Fig. 2a. During the monitoring period the field was irrigated early in July 2012.

The data were collected from 15 June 2012 to 15 November 2012 under different conditions of soil moisture. The ERI data were collected in a few campaigns from 29th June to 6th November; in the latter case TDR data were also collected. Moreover, the GPR data were collected on 2nd October. Simultaneous volumetric water contents (VWC) were measured in 13 points distributed in different locations within the parcel (Fig. 1), with capacitance sensors at 0.15 m and 0.45 m depths below the ground surface. The VWC data at 0.45 m depth are collected automatically every hour, while the VWC values at 0.15 m depth are measured manually almost every fifteen days.

The water table levels were measured as well; the differences between ground and water table levels vary from almost 0.10 m to 1,4 m (Fig. 2b).

Five ERI sections were acquired using 48 electrodes with a spacing of 0.5 m and Wenner array, to yield a high-resolution resistivity model down to 2.5 m bgs. GPR measurements were performed following a 17 × 17 lines square grid pattern, with a spacing of 1 m between the acquisition tracks, so that the covered area measured 16 m × 16 m (Fig. 1).

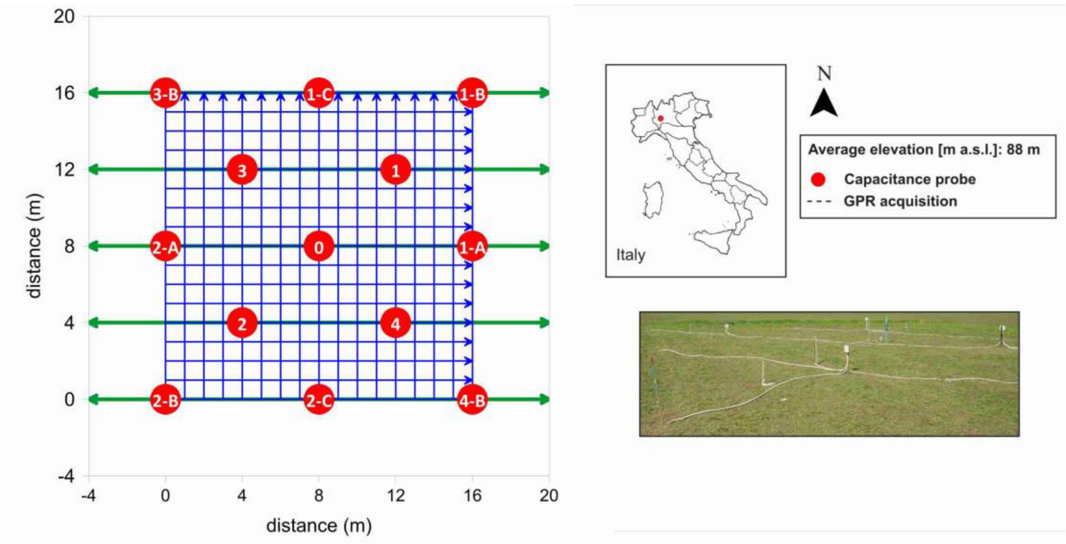

Fig. 1. The experimental site. The sampling locations are reported in red dots, while the dashed grey lines indicate the GPR acquisition tracks.

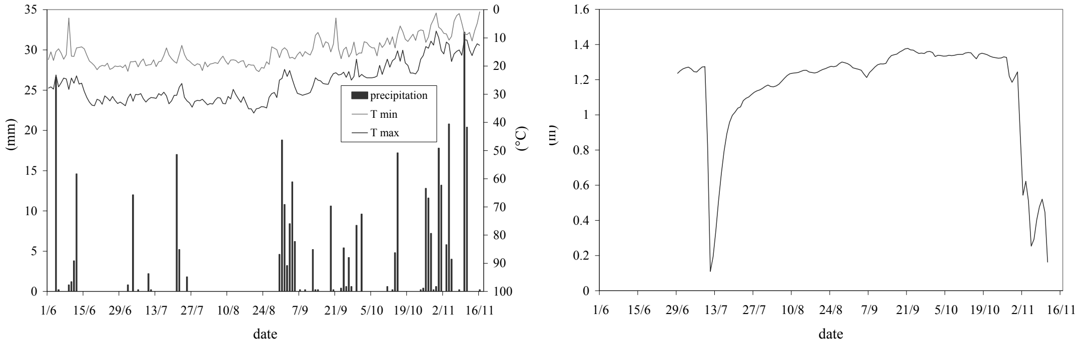

Fig. 2. Description of the experimental site. Daily data from June 2012 to November 2012: (a) precipitation (mm) and temperature (°C); (b) differences between ground and water table levels (m)

2.2. The water content measurements

In this study only the VWC data at 0.15 m depth are considered. The capacitance probe WaterScout SM100 (by Spectrum Technologies Inc.) was used to measure VWC. Undisturbed soil cores of the same volume of the support explored by the probe were collected as close as possible to the sampling points throughout the monitoring period, on some dates of the spatially distributed campaigns. The gravimetric water content (GWC) was measured in laboratory and transformed in volumetric water content to determine the site specific calibration curve. The direct (GWC) and indirect (VWC) soil moisture measurements well agree, since the mean absolute relative error and the coefficient of determination are respectively 13% and 0.89. The mean absolute relative error between the calibrated VWC values (hereinafter VWC_{adj}) and the reference volumetric water contents GWC is 5%, while the mean error is -0.0003 and the error variance is 2.5. The statistical description of the volumetric water contents for the campaigns on 2nd October and 6th November is reported in Table 1. For the campaign on 2nd October the variance of both VWC and VWC_{adj} is less than the error variance, showing that a more accurate probe would be required to detect the spatially correlated variability of VWC. The 95% confidence intervals for the VWC_{adj} values show the statistical significance of the VWC_{adj} as estimate of the actual VWC (Fig. 3).

2.3. The Ground Penetrating Radar

In this work, a GPR with two ground-coupled antennae at 600 MHz and 1600 MHz centre frequencies (RIS/MF system manufactured by IDS S.p.A., Italy) was used. According to the objectives of this study, only the mono-static channel 600 MHz-600 MHz was processed, whereas the mono-static signal at 1600 MHz and the two bi-static signals were used for cross-checking. Two GPR-based methods were used to analyze the subsurface moisture content. The first one is based on the evaluation of the electric permittivity from the signal amplitude attenuation. In particular, it is well known that the amplitude of the received GPR signal is affected by the electromagnetic characteristics of materials . In that respect, due to the high difference between the electric permittivity of water (ε_{water}=81) and dry soil ($\varepsilon_{dry\ soil}$=3-8), the variation of amplitude is very sensitive to the presence of water. More in depth, high difference between the electric permittivities of adjacent interfaces causes high amplitude reflections, therefore an increase of moisture content can be registered. Following this principle, the electric permittivity is retrieved from the variation in the amplitude of reflections from the subsurface, in relation to a reference amplitude from a perfect electric conductor, consisting of a large metal sheet [28]:

$$\varepsilon_r = \left[\frac{1 + A_0 / A_m}{1 - A_0 / A_m} \right]^2 \tag{1}$$

where ε_r is the relative electric permittivity of the soil laying above the reflecting surface, A_0 [V] and A_m [V] are the amplitudes of reflection from the real surface and from the metal plate, respectively. Eq. (1) can be used although information on subsurface thicknesses of layers and the wave velocity through the ground are missing. Once the electric permittivity is estimated using Eq. (1), the volumetric water content w [$m^3 \cdot m^{-3}$] is computed using the Topp petrophysical relationship [21] as follows:

$$w = -0.053 + 0.0292 \cdot \varepsilon_r - 5.5 \cdot 10^{-4} \cdot \varepsilon_r^{\,2} + 4.3 \cdot 10^{-6} \cdot \varepsilon_r^{\,3}$$

The use of the coefficients of Eq. (1) has been verified with respect to the nature of the investigated soil. From now on, this method is referred to as the “reflectivity” method. Another method used to analyze the soil moisture variability, which is referred to as the “scattering” method from now on, is focused on the Rayleigh scattering of the signal, on the basis of the Fresnel theory [29]. In GPR surveys, a three-phase porous medium, typically composed of soil matrix, air and water, causes multiple scattering events. In the Rayleigh scattering domain the dimensions of the non-uniformities (e.g. water droplets and soil particles) are expected to be much smaller than the wavelength of the signal.

In this approach, the signal processing is carried out in the frequency domain. Past studies considering various types of unsaturated porous media, have shown that both the soil texture and local variations of moisture content cause a different scattering of the various components of the frequency spectra. Therefore, the comparison of the frequency spectra between the transmitted and received signals, allows to retrieve reliable information on the water content below the soil surface. In that respect, the peak of frequency can be considered as a comprehensive indicator, negatively related to the moisture content.

Table 1. Statistical description of the VWC values (%) for the campaigns on 2nd October and 6th November.

	VWC 2 Oct	VWC 6 Nov	VWC_{adj} 2 Oct	VWC_{adj} 6 Nov
Min	24.9	25.4	28.9	29.3
Max	28.8	38.8	31.6	38.4
mean	27.1	32.6	30.4	34.2
variance	1.9	15.7	0.9	7.2
number of points	10	12	10	12

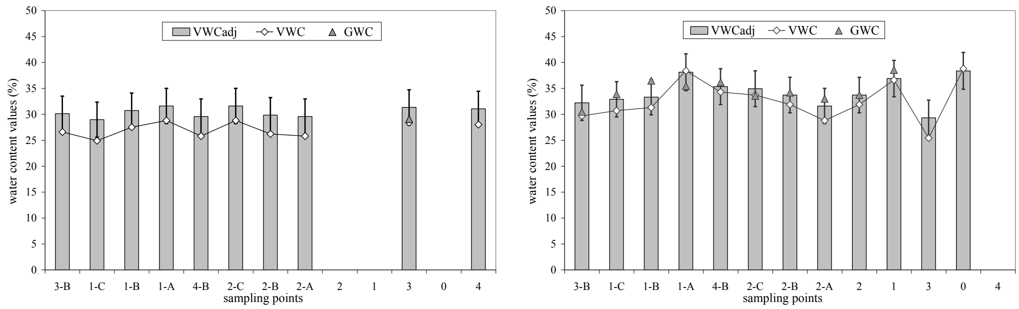

Fig. 3. Comparison between VWC, VWC_{adj} (the 95% confidence intervals are reported) and GWC values (%) for the campaigns on: (a) the 2nd October; (b) the 6th November.

3. Results and discussion

3.1. Soil heterogeneities detected by ERI

The subsurface of the experimental site is characterized by low electrical resistivity, typical of soils with high content of clay and silt. In these sedimentary environments surface conduction, produced at shale-grain interfaces by the excess of negative charges of clay particles forming an electrical double layer, is the dominant conduction process [26,30]. The ERI sections clearly depict the local water table as a horizontal interface marked by a decrease of electrical resistivity. As an example, the results obtained for the central section on 19th October and 6th November are compared in Fig. 4. The almost horizontal discontinuity, that separates shallow bodies with resistivity less than 40 Ωm from the deeper materials with higher resistivity, can be interpreted as the signature of the water table which approximately raised from 1.0 m bgs to 0.5 m bgs in 18 days. These results are in good agreement with the position of the water table observed in a shallow trench dug a few meters from the ERI survey line as well as with the measurements reported in Fig. 2b. The interpolation of the vertical resistivity sections obtained from field data inversion permits to draw maps of the spatial distributions of electrical resistivity at different depths, a couple of which are shown in Fig. 5. The near surface volume, down to 0.2 m bgs, is characterised by fine-scale variability with high and low resisitivity anomalies. Such a very heterogeneous condition is probably due to the reworking of shallow materials due to agricultural activity. At 0.5 m bgs, the soil is more homogeneous but it is evident the presence of a linear structure within the parcel which resembles some man-made structure.

3.2. The spatial analysis of the VWC values

The VWC_{adj} values for the campaign on 2nd October are not adequate to characterise the spatial correlation of water content, thus they are used just to provide a punctual checking of the water contents estimated from GPR data. The VWC_{adj} values for the campaign on 6th November are normally distributed (the Shapiro-Wilk test is 0.93 with p-value equal to 0.37); they are considered to analyse the structure of the water content spatial variability (the variogram model is spherical, with range 9 m, sill 4.8 and nugget 0.6). Finally, the VWC_{adj} values are interpolated by kriging. The variability maps in Fig. 6 are estimated using 11 data points (the value in sampling point 3 is an outlier) with variance equal to 5.32. The uncertainty of the estimated VWC values is evaluated from the kriging standard deviation. The maximum standard deviation depends on the very few sampling points with distance from interpolated points less than the correlation distance (equal to the variogram range). The kriging standard deviation is comparable with the error standard deviation (estimated from the GWC values) where the density of data points is the highest. Thus the interpolation results are considered good given the limited number of measurement locations as well as the accuracy of the capacitance probe.

3.3. GPR relief

Fig. 7 presents the comparison between the interpolated maps of VWC from the "reflectivity" method and the "scattering" method, both derived from the GPR acquisition on 2nd October. Concerning the application of the "reflectivity" method, the field-average soil moisture equals about 28 (%), with a standard deviation of about 3 (%) (Fig. 7a). High water contents can be observed at two places at about 7 m from the northern edge of the surveyed area: one spot is located at about 5.5 m from the western edge and the second one at the eastern edge. Conversely, the driest areas are encountered in the middle of the western edge as well as near the south-eastern corner of the field.

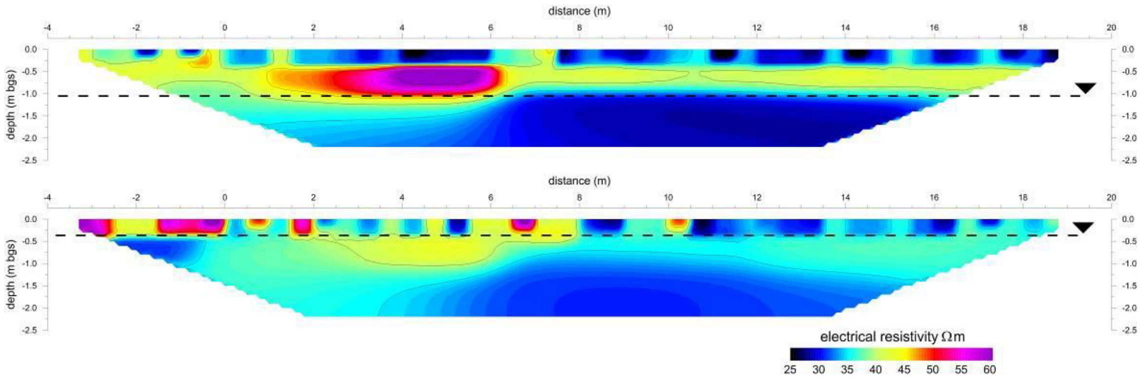

Fig. 4. Section distributions of the electrical resistivity (Ωm) detected in different soil moisture conditions: (a) on 19th October; (b) on 6th November

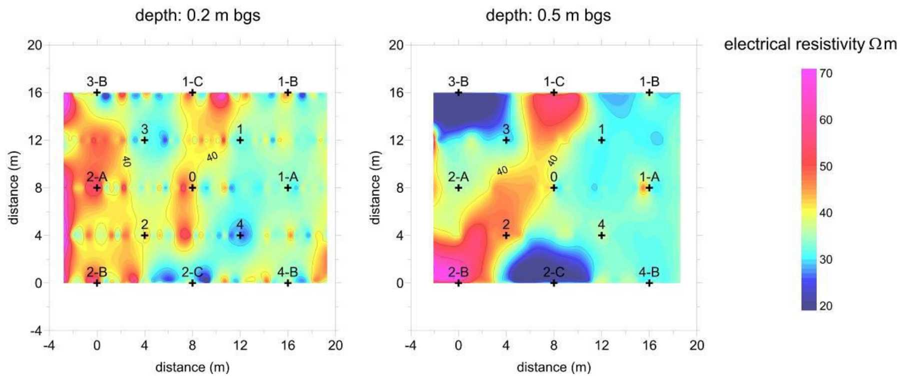

Fig. 5. Spatial distributions of the electrical resistivity (Ωm) detected on 6th November at different depths: (a) 0.2 m bgs; (b) 0.5 bgs.

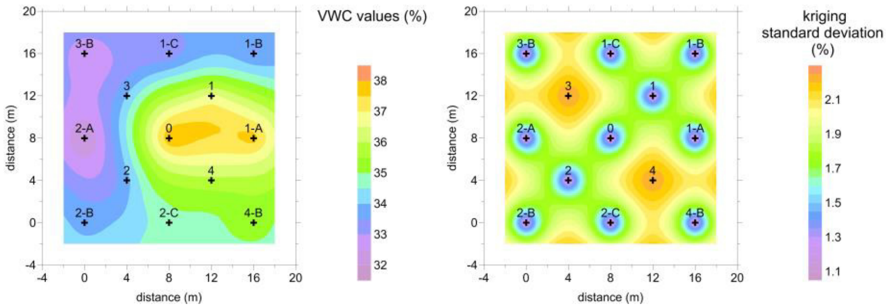

Fig. 6. Interpolated maps of the VWC_{adj} values for the campaign on 6th November calculated by kriging: (a) the estimated VWC values (%); (b) the kriging standard deviation (%).

Fig. 7b shows the interpolated map of VWC retrieved by the frequency peaks of the signals spectra using the “scattering” method. It is worth noting that the distribution of the frequency peaks was consistent with the theoretical expectations; in particular, a lowering of the peak of the frequency spectrum corresponded to an increase of the electric permittivity, as the moisture was expected to rise. Conversely, from the increase of the frequency peak and the lowering of the permittivity, it was expected a decrease of the moisture content.. The method reveal higher VWC values (field-average soil moisture equals about 32%), and a lower standard deviation (about 2.3%) compared to the VWC values from the “reflectivity” method. In any case, a relatively good agreement in the distribution of the VWC in the area is shown in comparing this map with Fig. 7a. In that respect, a clear match can be observed between the high moisture contents in the north-western part of the figures. More matches can be found in the middle of the western edge of both figures, as well as in the south-eastern corner of them.

3.4. Analysis of the water content variability

The VWC_{adj} distributions are compared with the variability maps of electrical resistivity and water content evaluated from the ERI and GPR reliefs, respectively.

The heterogeneity structures detected with ERI (Fig. 5a) are correlated with the variability map of water content obtained interpolating the VWC_{adj} values (Fig. 6). The correspondence between high resistivity values and low water contents in the left area is well defined.

The water contents estimated from GPR data are compared just locally with the VWC_{adj} values (Fig. 8). The observed discrepancies can be probably related to the different support scales of the GPR techniques, compared to the small-scale variability of soil moisture. Although the GPR-derived and the VWC_{adj} values are significantly different in Fig. 8a, the GPR are clearly useful to detect and characterise the variability of water content at small scale as shown in Fig. 7.

4. Summary and conclusions

We tested an alternative approach to monitor the soil moisture variability with non invasive surface geophysical techniques which permit to rapidly collect a large number of reproducible measurements. In particular we tested the Electrical Resistivity Imaging (ERI) and the Ground Penetrating Radar (GPR) techniques in a 20 m × 20 m parcel of bare sandy-loam soil located within a crop field in Northern Italy.

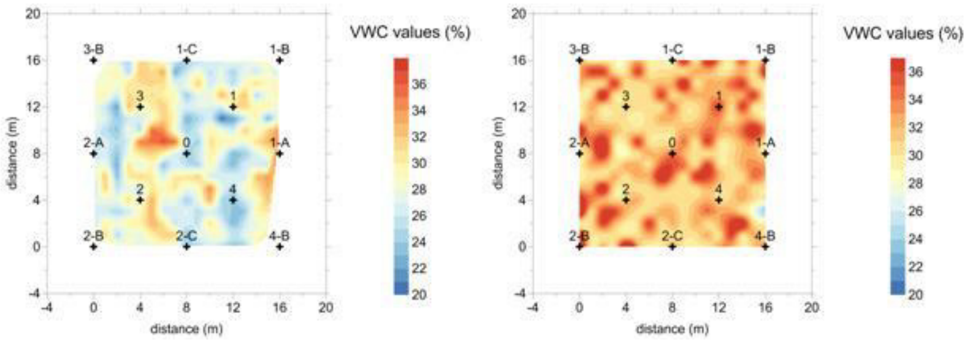

Fig. 7. GPR-derived interpolated maps for the campaign on 2nd October: (a) the estimated VWC values [%] from the "reflectivity" method; (b) the estimated VWC values [%] from the "scattering" method. .

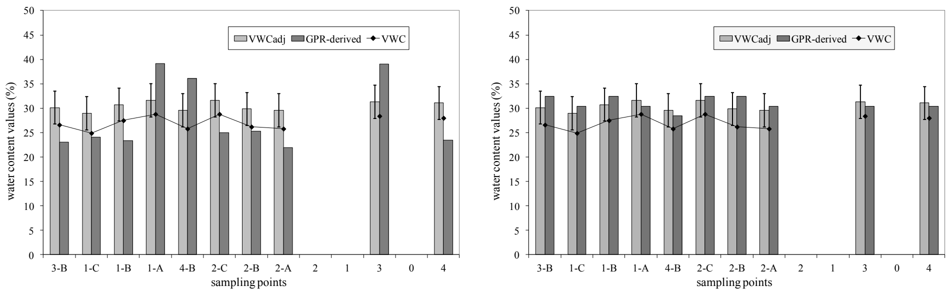

Fig. 8. Comparison between GPR-derived and VWC_{adj} values (%), the 95% confidence intervals for VWC_{adj} are reported: (a) GPR derived values from the "reflectivity" method; (b) GPR-derived values from the "scattering" method

The ERI data were collected in a few dates in 2012 from July to October, under different conditions of soil moisture, while the GPR data were collected in a single day in October. Moreover simultaneous measurements of the volumetric water contents (VWC) were taken with capacitance sensors at 15 cm and 45 cm depths in different locations within the parcel. The monitored soil zone is 1.5 m thick at most, between the ground surface and the water table.

The ERI well identifies the boundaries between different soil horizons as well as the structural soil characteristics resulting from agricultural practices. The variability maps of the physical properties provided by ERI and GPR techniques were compared with the VWC measurements. In particular the GPR reliefs showed to be useful to detect and characterize the variability of water content at small scale when the accuracy of the probe is not adequate to monitor the spatial correlation structure. Also the comparison with resistivity maps at different depths obtained from ERI is promising, as it showed a good relation between the spatial distribution of electrical resistivity and water content.

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