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Spatial description of the soil water dynamic by the electrical resistivity at the field scale

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Abstract

Since recently, geophysical methods enable the monitoring of some soil characteristics on a continuous space with a high resolution. However the interpretation of electrical measurements is difficult because the geophysical data are influenced by many soil variables, that vary, or not, with time. Our objective was then to use spatial measurements of electrical resistivity, to define zones of homogeneous electrical resistivity, to interpret them in terms of evolution of water content, and to compare them with a soil map. Our assumption was then that the time variation of electrical resistivity at the field scale was only due to the evolution of the soil moisture in our studied field. A time monitoring of the soil electrical resistivity and the soil moisture was realized during the year 2006, at four dates, both by the MUCEP device (MultiContinous Electrical Profiling), that gives measurements on a whole field area, and by local gravimetric measurements of the soil water content. Homogeneous zones were defined directly from measurements for the electrical resistivity, and after ordinary kriging for the water content. Our analysis of the spatial and temporal variability has permitted to discriminate three temporal homogeneous zones, both for electrical resistivity and the water content, that were mainly related to the soil map. The use of electrical measurements enables to directly describe the spatial and temporal evolution of soil water content at the field scale, and to describe some hydric processes, like lateral flows or upward capillary flows that would be difficult to derive from soil maps.

Keywords: field scale, time monitoring, soil water content, electrical resistivity, zones

1. Introduction

The soil subsurface water content variability requires a fine description in space and time. It is commonly obtained by invasive methods (gravimetric method, TDR measurements, neutron probe measurements). The latter give only punctual and restricted spatial and temporal information. In recent publications, geophysical and no invasive methods –electric and electromagnetic methods- have been described to quantify the soil state variables, as the soil water content, in a space continuum (Sheets and Hendrickx, 1995; Lambot et al., 2004; Guérin, 2005). One of them, the electrical resistivity ρ (ohm.m) -or DC method- is well adapted to characterise the soil subsurface and to describe soil properties, even if they are time-dependent. Recent technical developments (Dabas et al., 2001) enable to obtain accurate spatially continuous electrical estimates at the field scale. However the electrical resistivity depends on several chemical and physical soil variables that can interact. The influence of one soil parameter like the soil water content on the electrical resistivity is then hard to estimate. Nevertheless, when temporal electrical measurements are obtained by time monitoring, they should depend only on the soil parameters that vary with time, i.e. the water content, the temperature and the composition of the soil solution. If we are able to correct the effect of temperature and composition of the soil solution, the monitoring of electrical resistivity of soil could be interpreted in terms of water content.

Our study aims then at using the DC method to describe the spatial and temporal soil water dynamic. A monitoring is realised at the field scale by the MUCEP device, that gives spatial continuous measurements of the electrical resistivity. A temporal analysis of these data enables to define homogenous zones in terms of electrical resistivity and, as a consequence, in water content. The soil map obtained by conventional methods is compared with the map of homogenous electrical resistivity zones. The interest of a temporal monitoring of the electrical resistivity is discussed.

2. Material and methods

2.1. Characteristics of the studied soils

The study site is located in the Beauce region (France), on a fallow field of 2 ha. The soils are calcic or calcareous cambisols (FAO, 2006) developed in the Beauce limestone bedrock. The differences between soils depend on the rock content and thickness of the loamy-clay layer. From 39 boreholes, 8 soil units were defined on a soil map (Figure 1).

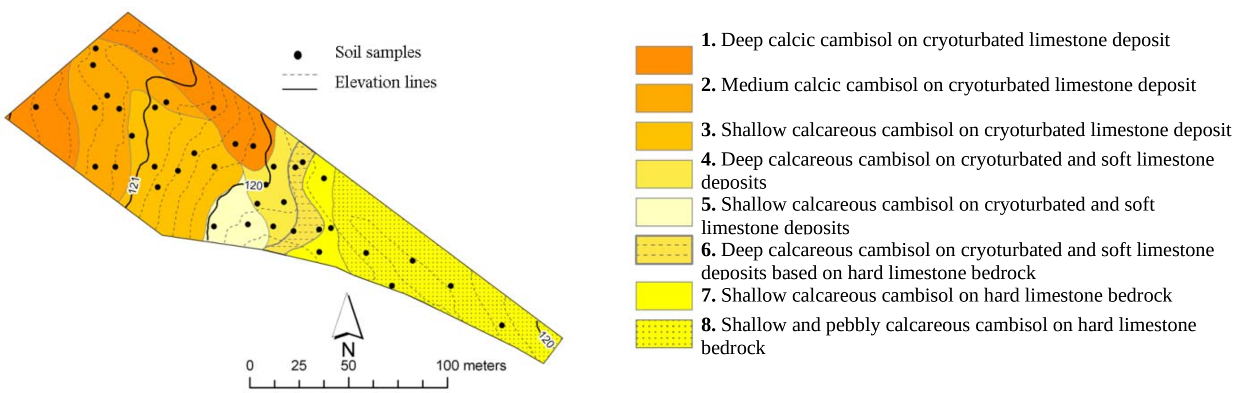

Figure 1: Soil map of the studied area. The black dots represent the locations of soil sampling.

2.2. Soil water content monitoring at the field scale

33 soil samples, located at different positions in the studied area, were taken to measure the gravimetric water content, depths: 0-0.30 m, 0.30-0.50 m, 0.50-0.70 m and 0.70-1 m depth. To be compared with the bulk electrical resistivity, mean values of soil water content were

calculated for depths 0-0.30 m, 0-0.50 m, 0-0.70 m and 0-1 m. These mean values were weighted with the layer thickness. The soil samples were collected at four dates in 2006: 12th of April, 01st of June, 30th of August and 24th of October.

2.3. Electrical time monitoring at the field scale

Electrical resistivitiy measurements were obtained at the field scale by the use of MUCEP (MultiContinous Electrical Profiling) device (Figure 2), at the same dates as the soil water content monitoring.

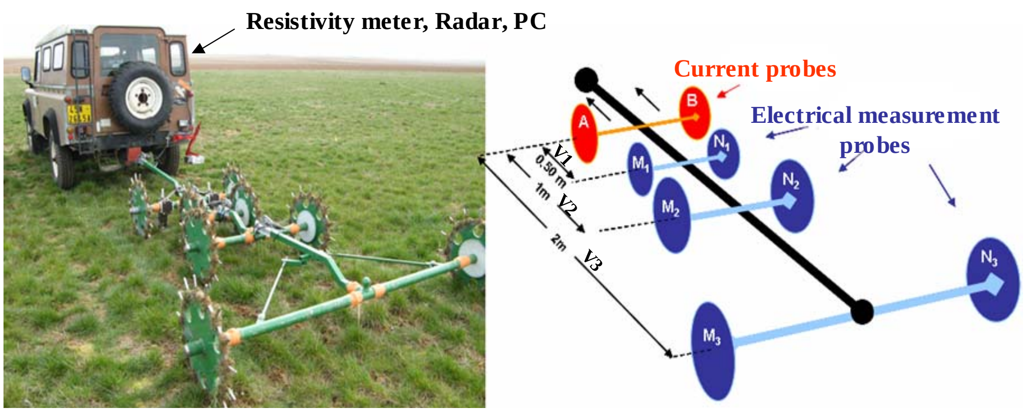

Figure 2: The Multi-Continuous Electrical Profiling device (MUCEP).

The MUCEP device is a mobile soil electrical resistivity mapping system, that comprises a multi-probe system of 3 arrays (V1, V2, V3 arrays) pulled by a cross-country vehicle. It is completed by a resistivity meter (10 mA, 122 Hz) and a Doppler radar which triggers a measurement every 10 cm along an electrical profile. The electrical measurements consist in apparent resistivity that is defined as the integrated value of the real resistivity over the soil volume comprised between the electrodes array. We assume that the arrays (V1, V2 and V3) measure “shallow depth”, “medium depth” and “deeper depth”. The electrical profiles were spaced of 2 m along parallel lines and are oriented SE-NW. All measurements were georeferenced by a dGPS (Trimble) device and recorded on a PC. The electrical resistivity measurements with the MUCEP system were recorded at the same dates as the water content measurements. At each date and for each array, a minimum of 52000 measurements were recorded. They were corrected for the temperature effect by the Keller and Frischknecht equation (1966):

$$\rho_{Tref} = \rho_m [1 + \alpha (Tm - Tref)]$$

with ρ_{Tref} the corrected electrical resistivity at the *Tref* reference temperature equal to 25°C, ρ_{Tm}, the observed electrical resistivity at the *Tm* measured temperature and α the temperature coefficient equal to 2 %.

2.4. Spatial and temporal variability analysis

For each date, the maps of water content and electrical resistivity were calculated by ordinary kriging with regular grids (respectively 5x5 m for the water contents and 0.5x0.5 m for the electrical resistivity).

The spatial analysis of the temporal variability of soil water contents and of the electrical resistivity was discussed by calculating the normalised temporal mean map from :

$$\overline{X_j} = \frac{1}{4}\sum_{i=1}^{4}\frac{x_{j,t_i} - \overline{x_{t_i}}}{s_{t_i}}$$

with x_{j,t_i}, the water content or the electrical resistivity at location *j* for the date *ti*, s_{t_i}, the standard deviation of the mean hydric or electrical state $\overline{x_{t_i}}$.

Negative (resp. positive) values for $\overline{X_j}$ suggested that the water content or the electrical resistivity measured at the location *j* at the date *ti* is always lower (resp. higher) than the spatial mean $\overline{x_{t_i}}$ at *ti*. The temporal maps were build with the same regular grids as the spatial analysis. They present no unit.

3. Results and Discussion

3.1. Statistical relationships between the electrical resistivity measurements and the soil water content

For each date, a regression analysis was realised between the electrical resistivity measurements (V1, V2 and V3 arrays) and the corresponding soil water content of four soil layers (0-0.30 m, 0-0.50 m, 0-0.70 m and 0-1 m). The linear determination coefficients and the Pearson correlation coefficient were calculated (Figure 3).

Whatever the soil layer water content, the determination coefficients are higher for the V1 array (about 40 % for the soil layers of 0-0.70 m) than for the others, except in June. This result suggests that the electrical resistivity measured by the V2 and V3 arrays are not really sensitive to the soil water content measured within one meter depth. We will focus then our analysis on the V1 array and on the soil water content of the 0-0.70 m layer in the following.

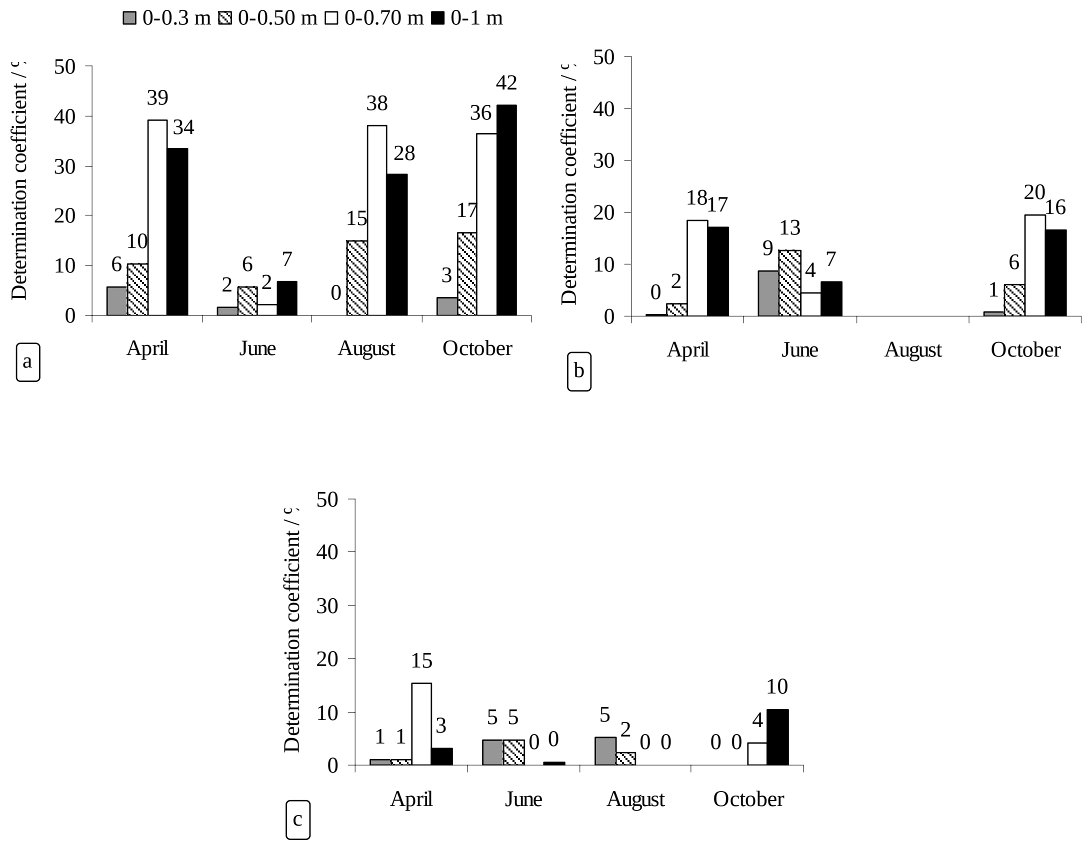

Figure 3: Determination coefficient (R^2) of the linear relationship between the electrical resistivity measurements and the soil water content for each soil layer thickness (0-0.30 m; 0-0.50 m; 0-0.70 m; 0-1 m) and at the four dates. a- V1 array; b- V2 array; c- V3 array.

3.2. Spatial analysis of the experimental data

Whatever the date, the maps of electrical resistivity show a similar spatial organisation, where three electrical zones can be defined (Figure 4): the highest values are located on the SE part of the studied zone (zone A) while the lowest values are located both in the middle of the site - along a corridor oriented North-South - and along the North border of the studied zone (zone B). In the W part of the studied zone, we see intermediate values (zone C).

Whatever the dates, we can relate the three zones (A, B and C) identified on the electrical resistivity maps to areas on the soil water content maps: the highest the electrical resistivity values (Figure 4), the lowest the soil water content values (Figure 5). However this spatial organisation corresponds to the soil types identified on the soil map (Figure 1). The zone A consists in the shallowest soils, formed on the Beauce limestone bedrock. The zone B corresponds to deep soils developed on the cryoturbated limestone deposit and on the soft limestone deposit. The zone C corresponds to soils not thicker than 0.50 m on the cryoturbated limestone deposit.

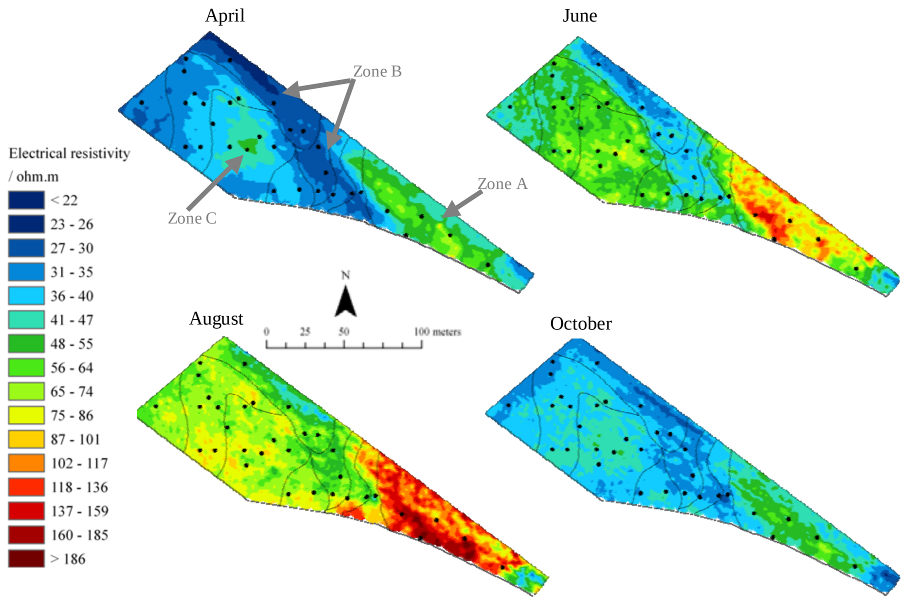

Figure 4: Maps of the electrical resistivity measured by the V1 array. The black lines represent the limits of the soil units. The black dots represent the locations of soil water content measurements.

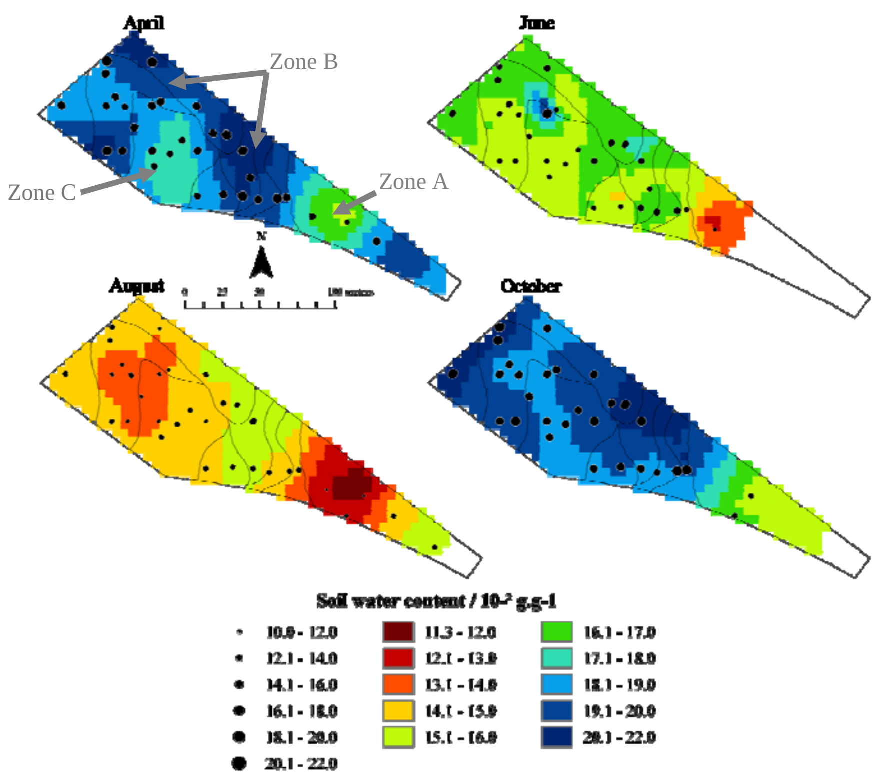

Figure 5 : Maps of the soil water content for the 0-0.70 m layer. The black lines represent the limits of the soil units. The black dots represent the locations of soil water content measurements.

The spatial variability of the electrical resistivity depends not only on the soil water content but also on the soil types and the thickness of the loamy-clay layer. When temporal electrical measurements are obtained by time monitoring, they should depend only on the soil parameters that vary with time, i.e. the water content.

3.3. Temporal analysis of the experimental data

When we compare 2 values of electrical resistivity at the same location, the difference between these 2 values does not depend neither on the soil type -that is supposed to be constant over the study- neither on the soil temperature -that is corrected- nor on the composition of the soil solution -that does not influence the results in this studied zone (Besson et al., submitted)-. Only the water content can explain the difference between the values. As a consequence, we make the hypothesis that a temporal analysis of the electrical resistivity could help in discussing the temporal variability of the soil water content.

Moreover the spatial estimation of the water content variability is difficult because of the low sampling density of the prediction set (the soil water content was even not determined on the SE part of the studied zone because of the difficulty to sample the hard Beauce limestone bedrock).

The zones B and C, identified on the electrical resistivity maps for each sampling dates, are clearly identified on the temporal electrical resistivity map (Figure 6a) and on the temporal soil water content map (Figure 6b). The zone B corresponds to negative temporal mean values for the electrical resistivity and to temporal positive mean values for the water content. On the contrary, the zone C consists in positive temporal mean values for the electrical resistivity and negative temporal mean values for the water content. In the zone A, the temporal mean values for the electrical resistivity are positive and high.

As a consequence, the zones of lower electrical resistivity are similar to the zones of higher soil water content and reversely, all over the time, for the zones B and C. In the zone A, we could then assume that the temporal mean values for the water content would be negative.

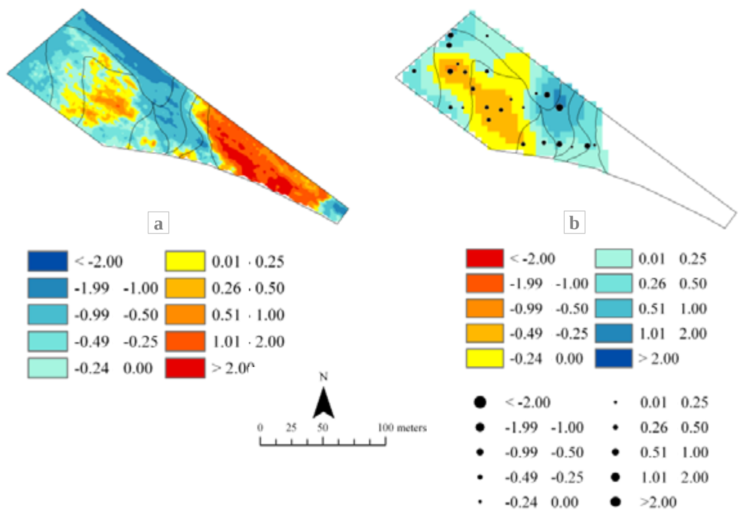

Figure 6: Maps of the temporal mean values of the soil water content for the 0-0.70 m layer **(a)** and of the electrical resistivity data measured by the V1 array **(b)**. The black lines represent the limits of the soil units. Black dots represent the soil water content measurements plots.

4. Conclusion

The electrical resistivity measured by the MUCEP device is well adapted to describe the spatial and temporal soil hydric variability at the field scale. The use of the MUCEP enables to extrapolate the temporal evolution of the water content in unknown zones.

At the field scale, we discriminate three electrical zones. They correspond to the soil water content contrasts found on the soil hydric maps, the lower soil water content values being related to the higher electrical resistivity values, and to the soil units.

The analysis of the temporal means of electrical resistivity and water content shows a similar spatial organisation: the zones that present, over the time, low soil water contents correspond to those that present, over the time, high electrical resistivity. These zones can be related to the soil units. As far as the hydrodynamical behaviour of soil is concerned, our temporal analysis of the evolution of the water content shows that the flows in our studied field are probably only vertical, without any lateral flow.

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