In situ temporal and spatial monitoring of the structure of a compacted and cultivated loamy soil by the 2D ERT method

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Abstract
Temporal and spatial monitoring of soil structural heterogeneity is useful to predict physical changes in soils. Usual methods implemented to characterise soil structure are generally destructive and time-consuming. Further technical solutions are then required to describe rapidly the soil structure without any disturbance. Electrical resistivity tomography (ERT) was proven to be efficient technique for detecting accurately zones with contrasted bulk density. Consequently space and time changes in soil structure might be characterized by ERT. We aimed then at testing this possibility by using the 2D ERT method.

We have monitored for 8 months a typical Luvisol by ERT. The soil was initially and locally compacted by a heavy tractor in the objective of creating zones of high bulk density. The studied plot encompassed bare soil and wheat crop. ERT results indicated the soil drying process which occurred in summer and particularly under wheat crop. We show also that electrical resistivity was higher in summer with local zone of very high resistivity probably due to soil cracking.

Introduction
Soil structure *i.e.* the arrangement of soil particles in space (Guérif 1987) is one of the factors controlling the physical quality of soils. In agricultural context, soil structure changes in space and time as function of plants growth, earthworm's activity, tillage, and climate. Compaction related to in-field traffic can modify significantly structure of cultivated layers in increasing bulk density. Soil compaction results in physical soil degradations as well in agronomic and environmental problems. Solutions are then required to characterise spatial and temporal changes in soil structure. Several methods were already developed to describe structural components at the profile scale (*i.e.* at macrostructural scale). For instance, these last ones are based on the visual description of a soil pit (Roger-Estrade *et al.* 2004), on soil sampling and measurements of soil properties such as bulk density, porosity, water retention, and penetration resistance, or on characterisation of the water infiltration. However these methods disturb soil and are also time-consuming. As a result, they cannot be implemented (or otherwise hardly) for a spatial and temporal monitoring of the soil structural heterogeneity.

Reversely electrical resistivity was proven to be a useful and efficient technique for soil structure description (Besson *et al.* 2004; Séger *et al.* 2009) at scale of entire soil profile. Electrical resistivity of soils depends on several soil parameters as, for instance, the volumetric clay and water contents, according to preferential electrical pathways within pores filled in water and at the surface of clay particles. Consequently, electrical resistivity should depend on soil bulk density and more generally on soil structural changes in space and time.

We aim then at examining the efficiency of Electrical Resisitivity Tomography (ERT) technique for characterising space and time changes of the soil structure within tilled layer of agricultural field, *i.e.* changes in soil macrostructure due to traffic (compaction) and climate activity (crack formation). The studied site presents a Luvisol (Beauce region, France).

This work corresponded to a section of the FP7-DIGISOIL project on "Integrated system of data collection technologies for mapping soil properties".

Materials and methods

Experimental site

The experiment was conducted in Beauce region (France). The soil was a typical Luvisol. The composition of the tilled layer (0-30 cm depth) was 170 g kg^{-1} of clay, 780 g kg^{-1} of silt and 50 g kg^{-1} of sand. A subplot of 25 m x 7.20 m was chosen for the study (Figure 1).

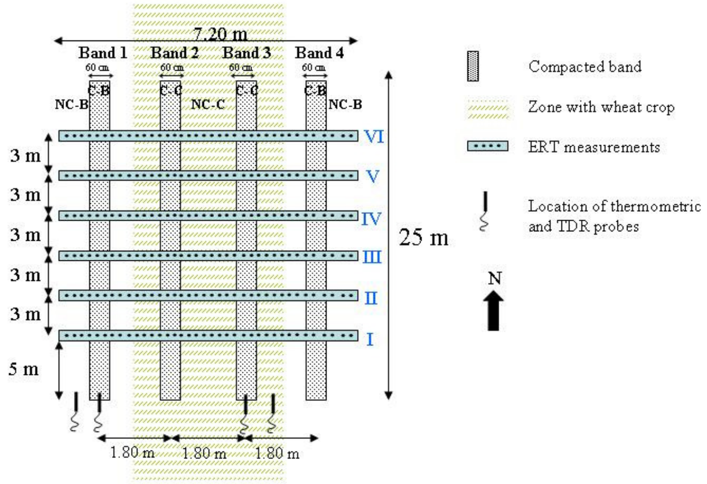

Figure 8. Design of the experiment

We created four compacted bands (Band 1, Band 2, Band 3, Band 4) by wheeling at water field capacity (mass water content equal to 23%) with a heavy tractor. We obtained then zones highly compacted (zones C) under wheel tracks and non-compacted zones (NC) outside of bands. Half part of the studied zone was cropped by wheat (zone C) in view of accelerating the drying up of the soil. This was located in the Central part of the study plot. The other part was conducted on bare soil (B). Finally the study gathered four modalities:

C-C: Compacted and wheat crop
C-B: Compacted and bare soil
NC-C: Non-compacted and wheat crop
NC-B: Non-compacted and bare soil

The experiment have been realized for 10 months, i.e. from March 2009 (sowing operation) to December 2009. The wheat yield was done in July 2009. From April to October, the soil was relatively dried and cracked. From November to December, the soil was in a wetting period due to rainfalls (this period was still not analysed here).

Electrical resistivity measurements

Electrical resistivity is a measure of the restriction of the media to an electrical flow artificially created and applied to soils. We used Electrical Resistivity Tomography (ERT) technique and interpreted apparent resistivity into 2D inverted resistivity models using inversion algorithm.

ERT measurements were realised by a system of 72 electrodes spaced 0.10 m apart, connected to a SyscalPro resistivity meter (Iris Instrument, Orleans, France). Electrodes configuration was Wenner type. ERT measurements were realized all along the lines I to VI (see Figure 1), perpendicular to the traffic direction. For each line, ERT was measured twice a week or twice a month from March to December.

Apparent resistivity were inverted and imaged by the RES2DINV software (Loke and Barker 1996) with "model refinement" option (cells with widths of half the unit spacing) and "robust inversion" (Claerbout and Muir 1973).

Characterisation of the soil structure

After ERT measurements and at similar location, i.e. along the lines I to VI, soil structure was also characterised by usual and destructive methods of structural description as the morphological description detailed by Roger-Estrade *et al*. (2004). With this method, the zones showing different degrees of compaction were visually identified and ranged into macroscopic features. Once the morphological profiles ended, bulk density was also determined on undisturbed soil cores sampled in pits. The spatial and temoral monitoring have been then realized along lines as mentioned above and at regular dates for the entire experimental period.

1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Ancillary data
Because of their influences on electrical resistivity, the soil temperature and the volumetric water content were recorded during the experiment. They were measured hourly respectively by thermometric probes and by TDR probes during the entire period of the experiment. The probes were installed at several depths (from 5 cm to 55 cm) for the four modalities (C-C; C-B; NC-C; NC-B), close to the studied plot but far enough to preclude interactions with ERT measurements.
The data of temperature enabled us to correct the temperature effect on ERT (Campbell *et al*. 1948).

First Results

Concerning the characterisation of the soil structure, large compacted zones (0.60 m x 0.30 m) were identified at the position of wheel tracks. Mean value of bulk density measured in these compacted zones was equal to 1.55 $g.cm^{-3}$ whereas it was equal to 1.35 $g.cm^{-3}$ in the non-compacted zones. Figure 2 shows the water content profile measured at two dates: 10th July 2009 and 18th August 2009.

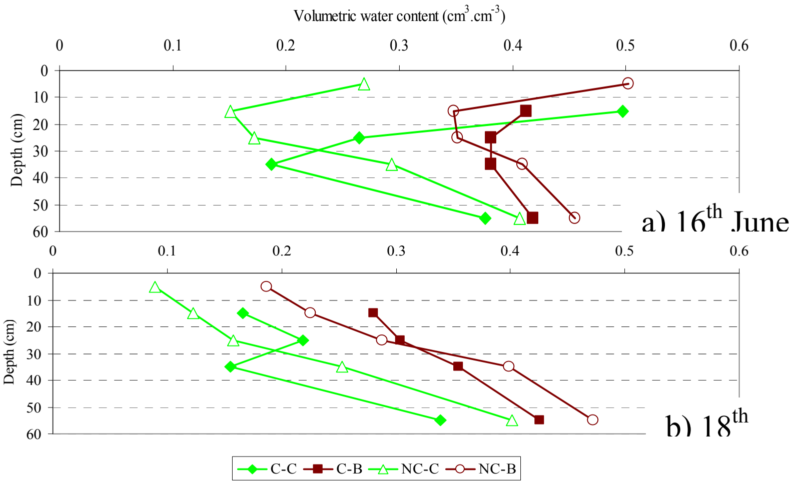

Figure 9. Water content profiles measured (a) the 16th of June 2009 and (b) the 18th of August 2009. The reference depth is the soil surface for C and NC zones.

For the two dates, we can observe crop effect on soil moisture: water content was small when the soil was cultivated. This result can be explained by higher evapotranspiration in the cropped zone than in the bare soil during the dry period.
The temporal monitoring of water content showed also that soil was dry in August, in particular in soil surface (5 cm and 15 cm depth) according to climatic conditions.
Water content was higher in the compacted zone than in the non-compacted zone for the depth up to 25-30 cm. Reversely water content was higher in the non-compacted zones for deepest layers (25-30 cm depth). Similar results were obtained for gravimetric water content (not showed here).

Results of ERT measured the 10th of June 2009 and the 18th of August 2009 along the line III are presented in Figure 3.

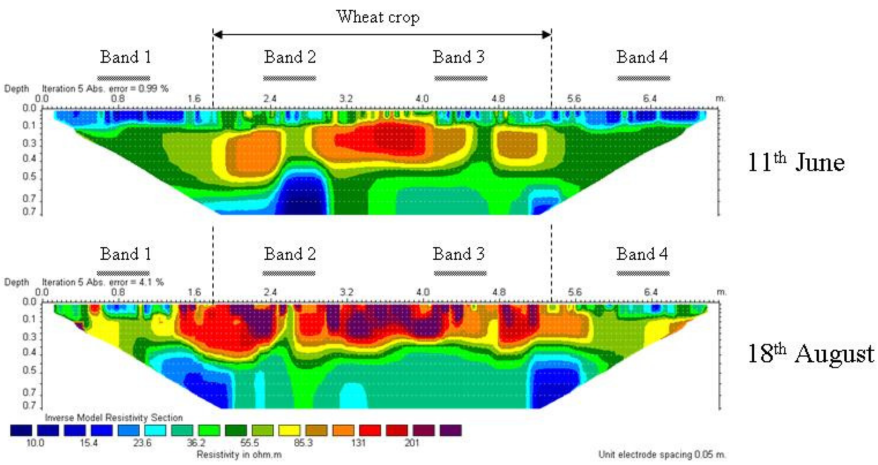

Figure 10. 2D ERT measured along the line III (a) the 10th of June 2009 and (b) the 18th of August 2009. Grey lines (Band 1, 2, 3 and 4) show the location of compacted zones.

We can identify compacted bands on ERT and in particular in near soil surface (from about 0 to 0.1 m depth. Indeed resistivities were small with values close to 15 ohm.m.

Reversely, high values of resistivity increasing with time were encountered in the first 40 centimetres of soil and in the central area of ERT (between 1.6 and 5.6 m). This zone corresponded to the cropped system which was propably responsible for a huge drying of the soil.

To comfort ERT results as obtained in field conditions, we have realized additional laboratory experiments which consisted in measuring electrical resistivity on soil cores at given bulk density and for a water content range generally encountered in field. We aimed then at better describing the relationship between geophysical data and soil variables of interest, i.e. the bulk density and soil water content, for such type of soil. We could then observe, for instance, that electrical resistivity varied from 20 to 70 ohm.m when the bulk density was equal to 1.45 g.cm^{-3} and when water content ranged from 10% to 22%. As a consequence, the high values (up to 250 ohm.m) obtained in the central area of ERT (as shown on Figure 3b for the 18th of August 2009), could not be explained only by drying. Another physical process could interact on resistivity, i.e. soil cracking. Indeed cracks are filled in air. They represent then structural components electrically resistant.

Conclusion

This study aimed at monitoring soil structure in time and space in 2D by ERT technique. ERT results shows that wheat crop is responsible for a huge drying of soil. Very high values of electrical resistivity measured in August could be explained by soil cracking. This process cannot be detected by usual and destructive methods. Electrical Resistivity Tomography appears then as a promising and useful tool for in-situ non-destructive temporal monitoring of soil structure.

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