

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Three-dimensional monitoring of soil water content in a maize field using electrical resistivity tomography

L. Beff¹, T. Günther², B. Vandoorne¹, V. Couvreur¹, and M. Javaux^{1,3}

¹Université catholique de Louvain, Earth and Life Institute, Louvain-la-Neuve, Belgium

²Leibniz Institute for Applied Geophysics, Hannover, Germany

³Forschungszentrum Jülich GmbH, Agrosphere IBG-3, Jülich, Germany

Received: 26 May 2012 – Accepted: 13 June 2012 – Published: 12 July 2012

Correspondence to: L. Beff (laure.beff@uclouvain.be)

Published by Copernicus Publications on behalf of the European Geosciences Union.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

A good understanding of the soil water content (SWC) distribution at the field scale is essential to improve the management of water, soil and crops. Recent studies proved that electrical resistivity tomography (ERT) opens interesting perspectives in the determination of the SWC distribution in 3 dimensions (3-D). We conducted this study (1) to check and validate the sensitivity of ERT for monitoring SWC distribution in a maize field during the late growing season; and (2) to investigate how maize plants and precipitations affect the dynamics of SWC distribution. We used time domain reflectometry (TDR) measurements to validate ERT-inverted SWC values. We also calculated the evolution of water mass balance to check whether ERT was capable of giving a reliable estimate of soil water stock evolution. We observe that ERT is able to give the same average SWC as TDR ($R^2 = 0.98$). In addition, we showed that ERT give better estimates of the water stock than TDR thanks to its higher spatial resolution. The high resolution of ERT measurements also allows the discrimination of SWC heterogeneities. The SWC distribution shows that alternation of maize rows and inter-rows is the main influencing factor of the SWC distribution. The drying patterns are linked to the root profiles, with drier zones under the maize rows. During small dry periods, the SWC decrease occurs mainly in the two upper soil horizons and in the inter-row area. At the opposite, precipitations increase the SWC mostly under the maize rows and at the upper soil layer. Nevertheless, the total amount of rainfall during the growing season is not sufficient to modify the SWC patterns induced by the maize rows. During the experimental time, the SWC redistribution hardly occurred from maize rows to the inter-rows but lateral redistribution from the inter-row to the maize rows induced by potential gradient generates SWC decrease in the inter-rows area and in the deeper soil horizons.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

The soil water content (SWC) controls important physical, chemical and biological processes occurring at the Earth surface: plant growth, solute transport, precipitations, runoff, erosion, and ultimately pedogenesis (Western et al., 2003). Its spatial and temporal variability is governed by the variability of soil properties and by the heterogeneity of the boundary conditions including the water sink/sources. The SWC distribution dynamics is therefore linked to spatial patterns of the processes generating/destroying variability (Teuling and Troch, 2005). The SWC distribution affects and is affected by various hydrological processes as the rain repartition between infiltration and runoff (Merz et al., 2006; Norbiato et al., 2009), the drainage, the pollutant dispersion (Flury et al., 1995) and the groundwater recharge. All these processes interact in agriculture as influencing irrigation scheduling (Clothier and Green, 1994) or precision farming and in environmental engineering as the control of groundwater pollution (Mooney and Morris, 2008).

At the field scale, crops are one of the main factors affecting SWC distribution. Amongst others, plant canopy influences the rainfall repartition at the soil surface (Hupet and Vanclooster, 2005), root water uptake generates drying patterns (Coelho and Or, 1999; Garré et al., 2011; Green et al., 2006; Li et al., 2002; Oliveira et al., 2005; Hupet and Vanclooster, 2005) and root channels may induce preferential fluxes (Devitt and Smith, 2002; Gish et al., 1998). All these factors create SWC heterogeneities in the three dimensions (3-D). The proper understanding of the drivers of SWC distribution dynamics is therefore crucial for accurate modeling (Western et al., 2003). Yet, quantifying soil moisture in unsaturated environments is difficult due to the complexity of unsaturated hydrologic systems and problems associated with obtaining accurate and spatially representative measurements of soil moisture in a heterogeneous environment (Schwartz et al., 2008). It is therefore challenging to quantify the SWC variability at the field scale.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Classical methods as gravimetric measurement with soil cores (Sharp and Davies, 1985), neutron probes (Hupet and Vanclooster, 2002; Koumanov et al., 2006) or time domain reflectometry (TDR) (Hupet and Vanclooster, 2002; Jacques et al., 2001; Robinson et al., 2003; Walker et al., 2004) are known to determine correctly the SWC.

The advantages of these methods are their robustness but they give only local measurement. Moreover, gravimetric measurement is destructive and TDR installation induces soil perturbation. At the opposite, remote sensing methods can cover large areas without soil perturbation. But they suffer from several disadvantages: measurements capabilities are limited at a few cm depths, over dense vegetation cover, by soil roughness, and the within pixel soil moisture variability can not be obtained (Minet, 2011). Proximal soil moisture sensing, as ground penetrating radar (GPR), electromagnetic induction (EMI) and ground-based radiometers, make possible the characterization of soil moisture at an intermediate scale between remote sensing and invasive sensors. But these sensors give only measurements in two dimensions (2-D). Moreover, GPR performance decreases in electrically conductive media such as fine-textured soils (Garré et al., 2011).

In the two last decades, electrical resistivity tomography (ERT) has been used in the determination of transport processes and SWC distribution. This technique was successfully used in solute transport experiments in bare soil lysimeter (Binley et al., 2002; Koestel et al., 2008, 2009a, b), in cropped lysimeter (Garré et al., 2010), in large experimental tank (Slater et al., 2002), in cropped field (Cassiani et al., 2006; Kemna et al., 2002; Vanderborght et al., 2005), and in forest (Oberdörster et al., 2010). Given the many factors influencing the soil electrical resistivity (Samouelian et al., 2005), soil conductivity was first used as a proxy for water content (Michot et al., 2001, 2003; Srayeddin and Doussan, 2009). However, more recently, a few studies tried to obtain the actual SWC distribution validated with TDR probes. Brunet et al. (2010) and Schwartz et al. (2008) inferred 2-D soil water content maps along transects. Werban et al. (2008) monitored 2-D electrical resistivity changes due to root water uptake in a 0.4 m × 0.5 m plot. Garré et al. (2011) investigated the 3-D soil water depletion in

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



a cropped lysimeter. These studies open interesting perspectives in using ERT for investigating the impact of plant on SWC dynamics. However, to our knowledge, no studies have focused yet on quantitatively monitoring the 3-D evolution of soil water content in a cropped field so far.

This study was conducted to determine the SWC distributions and evolution at the plot-scale during the late growing season of maize and to investigate how maize plants affect SWC patterns. This paper aims at (1) presenting and validating a methodology for using ERT at the plot scale, and (2) investigating how rainfall and root water uptake affect SWC distribution at that scale.

2 Material and methods

2.1 Experimental site

The experiment was conducted between the 23 July and 21 September 2009 in a field of 1.6 ha located in Corroy-le-Grand (Belgium), in the loamy region. The field was cropped with maize (*Zea mays* L.) from 14 April 2009 to 22 September 2009. Maize was sown with a row-spacing of 75 cm and around 13 cm in the row (100 000 plants ha⁻¹). This field is relatively flat, with slopes ranging between 0.2 % and 0.5 % (Weynants, 2011). The soil considered as a well-drained loam (Aba(b) according to the Belgian soil classification) is classified as a Haplic Luvisol (Soil Atlas of Europe, 2005) according to the FAO classification system. Three soil horizons were identified (Fig. 1). The Ap1 horizon (0–35 cm) has a strong blocky angular structure and contains many roots. The Bt1 horizon (37–75 cm) has a strong blocky angular structure. The Bt2 horizon (>75 cm) has a weakly blocky structure. Between the Ap1 and Bt1 horizons, there is a plough sole (35–37 cm), which is more resistant to penetration than the above horizon. The properties of the soil horizons are presented in Table 1. More information on this soil can be found in Weynants (2011).

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2.2 Experimental plot

In the field, an experimental plot of 2.5 m × 17 m was delimited and equipped at the mid July with 14 TDR probes, 132 surface and in-depth electrodes for conducting ERT, 7 temperature probes and 7 tensiometers (Fig. 2).

Seven water tensiometers were inserted vertically near the TDR probe trench to estimate water potential gradient and water fluxes (at depths 7.5 cm, 11.5 cm, 33 cm, 68.5 cm, 132.5 cm, 137 cm and 140 cm, with a spacing of 15 cm between each tensiometers). The tensiometers were installed in July in the middle of the inter-row to avoid damaging maize plants (Fig. 2).

The root colonization of soil in 2-D was characterized using Tardieu's profile method (Tardieu, 1988). A trench was dug perpendicular to maize rows (including 2 rows and 2 inter-rows) at the border of the experimental plot (Fig. 2). The three root profiles (DOY 225, 239 and 261 were done in the same hole, with a spacing ranging from 13 cm to 26 cm between each root profile in order to get two maize rows lined up. A grid with a 5 cm mesh was placed against the trench wall to count the number of roots present in each cell, resulting in vertical 2-D maps (1.5 m width and 1 m depth) of root impacts.

2.3 Time domain reflectometry

TDR method was used to monitor soil water content with a high time resolution ($\Delta t = 1$ h). Fourteen TDR probes (3 rods, 30 cm long, 0.5 cm rod diameter, 2 cm rod spacing) were horizontally installed at 4 different depths (10 cm, 30 cm, 70 cm and 125 cm) (Fig. 1) in a trench of 1 m wide and 1.30 m deep that was filled up after TDR installation. The TDR probes were inserted perpendicularly to the maize row with 7 probes behind maize row and 7 in the inter-row (Fig. 1). The probes were connected to TDR multiplexer (Campbell SDMX50, Campbell Scientific Lt., UK) controlled by an automatic data logger (CR10X, Campbell Scientific Lt., UK). TDR signals were generated and automatically analyzed by means of TDR100 system (Campbell Scientific Lt., UK). Measurements were monitored during 61 days under natural boundary conditions.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



TDR probes were calibrated using the Heimovaara (1993) method following the protocol described by Garré et al. (2006)

Topp's equation (Topp et al., 1980) was used to determine SWC, θ ($\text{cm}^3 \text{cm}^{-3}$) from the apparent dielectric constant, K_a , measured by TDR.

$$\theta = -5.3 \times 10^{-2} + (2.92 \times 10^{-2})K_a - (5.5 \times 10^{-4})K_a^2 + (4.3 \times 10^{-6})K_a^3 \quad (1)$$

We verified Topp's equation for our soil type in laboratory with undisturbed soil samples. By obtaining a root mean square error (rmse) of $0.0204 \text{ cm}^3 \text{cm}^{-3}$ between real and calculated SWC, we proved that this equation can be used in this study.

2.4 Electrical resistivity tomography

ERT was used to monitor the three-dimensional distribution of the bulk electrical conductivity (EC_b). Seventy-six surface electrodes (4 cm depth) and eight PVC sticks with seven electrodes each were inserted into the soil to form a regular grid of $1.95 \text{ m} \times 0.75 \text{ m}$ with an electrode spacing of 0.15 m (Fig. 3). Each stick is a PVC tube equipped with 7 stainless steel rings, used as electrodes, and positioned at 7 depths (5 cm, 15 cm, 30 cm, 50 cm, 75 cm, 105 cm and 140 cm depth). The stainless steel rings were a little bit larger (diameter of 46 mm) than the PVC tube (diameter of 45 mm) to improve electrode-soil contact.

2.4.1 Data acquisition

ERT measurements were conducted between the 13 August (DOY 225) and the 18 September (DOY 261). During this time, we performed 9 measurement frames using the ten-channel SYSCAL PRO instrument with the corresponding relay boxes (SWITCH PRO) for electrodes switching to carry out the ERT measurements (manufactured by Iris Instruments, France).

We developed, based on Bing and Greenhalgh (2000) and on field tests, a measurement scheme for our electrodes positions. The measurement scheme contains

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



a combination of various measurement types: (i) dipole-dipole measurements between the electrodes above 30 cm depth (76 surfaces electrodes and 24 upper sticks electrodes) with first, second and third spacing; (ii) Wenner measurements with sticks electrodes; (iii) cross-sticks measurements; and (iv) cross measurement between surface electrodes and stick electrodes. In order to assess data quality, all these measurements were realized in the forward and the reciprocal mode (Garré et al., 2010; Koestel et al., 2008; LaBrecque et al., 1996; Slater et al., 2000), where current and potential dipoles are switched. The measurement scheme took seven hours to run and contained 12 664 measurements.

2.4.2 Data filtering

We first removed all data outside of predefined bounds of measured voltage, injection current and geometric factor (larger than 400 m). We eliminated the data associated to a bad stacking factor (above 2%) given by the measurement instrument (SYSCAL PRO), which is the standard deviation of minimum 2 and maximum 4 stacks of a measurement (Slater et al., 2000). The next step was to eliminate the data with a reciprocal error ($e_i = R_{n,i} - R_{r,i}$), difference between the normal ($R_{n,i}$) and the reciprocal measurements ($R_{r,i}$), higher than 2% of the mean resistance (R_i). Then, we associated to each injection pair the mean between the normal and reciprocal measurements. Finally, we selected the measurements combinations that are present in each data frame and obtain 1994 data per measurement frame.

2.4.3 ERT inversion

To assess the soil EC_b distribution, we used a three-dimensional inversion of the ERT data obtained by the measurements. We inverted the ERT measurements (R_i , with $i = 1, \dots, N$) for each frame using a difference inversion (LaBrecque and Yang, 2001), with the first data set as reference. The code used for the inversion was BERT (Günther et al., 2006; Rücker et al., 2006) with an error-weighted, smoothness constrained,

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Occam-type algorithm. Occam's inversion finds the smoothest distribution of logarithmized resistivities ($\log \rho_j$, with $j = 1, 2, \dots, M$) which fits the measured data to a specified error level, ε_j . A Gauss-Newton scheme with global regularization is used to minimize the following objective function.

$$\phi = \|\mathbf{D}[\mathbf{d} - \mathbf{f}(\mathbf{m})]\|_2^2 - \lambda \|\mathbf{C}(\mathbf{m} - \mathbf{m}_0)\|_2^2 \quad (2)$$

where $\mathbf{d}$ is the data vector, given by $d_i = \log(G_i R_i)$ with $i = 1, 2, \dots, N$, parameters of the inversion and G_i the geometric factor, $\mathbf{f}(\mathbf{m})$ is the forward response for the model vector $\mathbf{m}$, given by $m_j = \log(\rho_j)$ with $j = 1, 2, \dots, M$, $\mathbf{m}_0$ is the starting and reference model (homogeneous for the first time step and its result for the others), and λ is a regularization parameter that determines the amount of smoothing imposed on $\mathbf{m}$ during the inversion. In this study, the λ was fixed for all the inversion. A constant value of 50 for λ was chosen to maximize the inversion quality considering a correct smooth effect of the image. The matrix $\mathbf{C}$ represents a discrete approximation of a partial differential operator of first order (Günther et al., 2006), and $\mathbf{D}$ is the error weighting matrix, given by

$$\mathbf{D} = \text{diag} [1 / \log(1 + \varepsilon_i)] \quad (3)$$

We assumed the errors to be composed of a percentage error of several per cent (p) and a voltage error (δU) (Friedel, 2003)

$$\varepsilon_i = p\% + \frac{\delta U}{U_i} \quad (4)$$

To determine the error level that should be used in the inversions, we realized an error analysis using the error model of Koestel et al. (2008) based on reciprocal data. The analysis for each data set separately gave us a p error ranging from 1 % to 3 % and a δU error of 0.5 mV. If we realized the analysis for all the data sets together, we obtained a p error of 1.7 % and a δU error of 0.76 mV. The percentage error of 1.7 is

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



relatively small. We then increased it to account the error sources that are not exposed by reciprocal error (Udphuay et al., 2011). For our inversion we used a percentage error of 2.7 % and a δU of 0.8 mV.

The deep electrodes of our system are ring electrodes located on a PVC stick. But, for the inversion, there are considered as point electrodes. To make this assumption, we first verified the effect of the electrodes sizes on the results of the inversion. The finite electrodes sizes were accounted for by taking the geometric factors of a complete electrode model (Rücker and Günther, 2011) with real geometries. We observed that the results considering the real electrodes sizes or point electrodes were similar.

To determine the quality of the inversion of ERT data with BERT, we used the relative root mean square error (rrms) and the χ^2 calculated as:

$$\text{rrms} = \sqrt{\frac{\sum_i \left[\frac{d_i - f_i(m)}{d_i} \right]^2}{N}} 100[\%] \quad (5)$$

$$\chi^2 = \frac{\sum_i \left[\frac{d_i - f_i(m)}{\varepsilon_i} \right]^2}{N} \quad (6)$$

The rrms and χ^2 of the ERT inversion were comprised 3.56 % to 10.43 % and 0.97 to 10.08, respectively, mostly close to the estimated error level.

2.5 Determination of the pedoelectrical relationship

Pedoelectrical models link bulk EC_b to variables influencing this conductivity: surface conductivity of the soil matrix, pore water conductivity, porosity of the soil, temperature and water content (Archie, 1942; Revil et al., 1998; Rhoades et al., 1989; Waxman and Smits, 1968). We derived three pedoelectrical relationships, one per soil horizon (Ap1, Bt1 and Bt2), based on the simplified Waxman and Smits model (Garré et al., 2011):

$$\sigma = a\theta^c + b \quad (7)$$

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



where σ (S m^{-1}) is EC_b , θ ($\text{cm}^3 \text{cm}^{-3}$) is SWC, and a (S m^{-1}), b (S m^{-1}) and c are fitting parameters. For determining parameters of Eq. (7), we used a TDR dataset from the same field, acquired during another field campaign in 2010.

We derived EC_b for the soil vicinity of the TDR rods (σ_{TDR}) from TDR signal attenuation using the following equation (Heimovaara, 1993; Mallants et al., 1996) as:

$$\sigma_{\text{TDR}} = \frac{K_p}{R_{\text{TDR}} - R_{\text{cable}}} \quad (8)$$

Where K_p is the cell constant of the TDR probe, R_{cable} is the resistance associated to the cable tester, multiplexers, and connectors. The value of R_{TDR} is derived from ρ_∞ , the reflection coefficient at very long time, and is defined:

$$R_{\text{TDR}} = Z_C \frac{(1 + \rho_\infty)}{(1 - \rho_\infty)} \quad (9)$$

where Z_C is the impedance of the TDR device, multiplexers, and cables. Both K_p and R_{cable} were determined for each probe individually using calibration measurements (Garré et al., 2006).

A temperature correction was applied to obtain the EC_b at 25°C (σ_{25}) from EC_b at the soil temperature T ($^\circ\text{C}$):

$$\sigma_{25} = \frac{\sigma}{1 + 0.02(T - 25)} \quad (10)$$

The three pedoelectrical relationships were applied on the EC_b , obtained by the inversion of ERT measurements, to transform it in SWC.

2.6 Validation of ERT soil water content

We validated our ERT methodology, first in a global way using the water mass balance and then by comparison with TDR measurements.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



To validate ERT in a global way, we compared the soil water stock change between two ERT measurement times to mass balance obtained from independent measurement:

$$P - D - \text{ETC} - \Delta S = 0 \quad (11)$$

5 where P is the effective precipitation (mm), D is the drainage (mm), ETC is the crop evapotranspiration, (mm) and ΔS is the variation of soil water content stock between the time (i) and the previous time ($i - 1$) (mm). The water stock was obtained by integrating ERT SWC from 0 to 140 cm depth. As an additional check, we also use the TDR data from the 2009 campaign to validate the stock from ERT data. We interpolated the
10 TDR SWC measured at 4 depths (10 cm, 30 cm, 70 cm and 125 cm) for the whole soil profile (from 0 to 140 cm depth).

The agro-climatic variables, i.e. dry and wet temperatures, shortwave radiation, wind speed and rainfall were measured in the meteorological weather station situated at 1.2 km distance from the study site. As the plot was flat and ploughed before sowing, runoff was considered as null. ETC (Fig. 5) was determined using the single crop
15 coefficient (K_c) approach and the reference evapotranspiration (ET_0), calculated using the Penman-Montheit equation (Allen et al., 1998) based on the meteorological station data. The drainage was estimated by the use of deep tensiometers (132.5 cm and 140 cm) for the hydraulic head gradient and the unsaturated hydraulic conductivity
20 obtained using the Mualem-van Genuchten model (van Genuchten, 1980) with the parameters presented in Table 1.

The second part of the validation of our ERT methodology is a comparison with the soil water content obtained by TDR. With TDR, we obtained SWC measurements on local places at four depths (Fig. 1) and at the opposite, ERT give a distribution of SWC
25 in 3-D on a 5 cm grid. To compare the results of the two methods, we (1) averaged the SWC measurements by time and by depth; and (2) observed the SWC evolution with the two methods for the areas situated under the maize rows and the inter-rows, respectively.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



To obtain the mean SWC we averaged the SWC obtained with all the TDR probes situated at the same depth (Fig. 1) and similarly, we averaged the SWC situated in the cells corresponding to the TDR depths (10 cm, 30 cm, 70 cm and 125 cm). By averaging the SWC, we will limit the effect of the within field SWC variability on the validation.

To verify that ERT is able to discriminate SWC differences in the soil profile, we compared the SWC evolution for both methods for the area situated under the maize rows and under the inter-rows separately. TDR measurements were realized directly in these two distinct areas (Fig. 1). For ERT, we considered a row area corresponding to 20 cm from each side of the maize row and an inter-row area of 35 cm in the middle. For each measurement time, we averaged the SWC obtained in each cells for the rows area and the inter-row area, respectively.

3 Results and discussion

3.1 Pedoelectrical relationships

The three pedoelectrical relationships obtained from TDR calibration are shown in Fig. 4. They were used to transform the ERT EC_b in SWC with the parameters of the simplified WS model presented in Table 2. The EC_b and SWC ranges of the first soil horizon are larger than for the two other soil horizons, demonstrating that the first soil horizon experienced larger variations of SWC. The pedoelectrical relationship for the third horizon is relatively flat for the EC_b range encountered during experimental time (between 0.01 S m^{-1} and 0.07 S m^{-1}). This denotes a high accuracy in SWC prediction in the third soil horizon for this range of EC_b . An attempt was made to split the pedoelectrical functions with and without the presence of roots, without any improvement, at the opposite of the observations made by Werban et al. (2008), who observed two distinct pedoelectrical relationships in presence or absence of roots. We then assume that the effect of soil horizons is more important than the roots effect on the discrimination of our pedoelectrical relationships.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In each soil layer, we observed rmse (Table 2) close to the ones obtained by Garré et al. (2011). These deviations can inflict small errors in the SWC determination. However, these rmse are similar to the rmse obtained with the TDR soil water content calibration ($\text{rmse} = 0.024 \text{ cm}^3 \text{ cm}^{-3}$). It suggests that a large part of the variation may be influenced by TDR uncertainty.

3.2 Validation of soil water content distribution measured by ERT

3.2.1 Water balance

Figure 5 shows the evolution of the boundary conditions of the experimental plot (P and ETC) and the water stock evolution for TDR and ERT measurements for the whole soil profile (between 0 and 140 cm depth). During the experimental period, the TDR water stock had a general decreasing trend, ranging from 453 mm (DOY 205) to 417 mm at the end of the period (DOY 264) due to ETC, with local increases due to the precipitations. The water stock for ERT was higher than the one obtained by TDR. The deviation between ERT and TDR soil water storage ranged between 2.4 mm and 15.2 mm. This is in the same range than Hupet et al. (2004), who showed that uncertainty in a soil water storage estimate for their considered experimental measurements in terms of standard deviation range between 9.72 and 10.37 mm. To quantify the error linked to TDR interpolation, we calculated the water stock from ERT data based on four local values only (corresponding to TDR probes depths), and we interpolated them as for TDR measurements. We used the average SWC obtained by ERT at the corresponding TDR probe depths. When only four local measurements were used for estimating water storage, the deviation between TDR and ERT water stock ranges between 1.46 mm to 8.43 mm. The ERT SWC based on four local values is then closer to the TDR water stock, especially at the beginning of the ERT measurement time. We then assume that the difference between ERT and TDR water stock is partly due to our interpolation method.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



We estimated the error associated to the ERT storage by checking the mass balance in Eq. (11) for the eight periods between our ERT measurement times. The black line of Fig. 6 represents the difference between the input and stock change and the output. If there is no error in the different variables of balance and if the water stock calculated with the ERT measurement is correct, the black line should be equal to zero. For most of the dates, the water balance was close to zero (the deviation was between 0.01 mm and 3.01 mm), indicating a very good estimate of all the mass balance terms. The small difference could be associated (i) to the ERT uncertainty due to the use of an empiric pedoelectrical relationship (Laloy et al., 2011) and the imperfect inversion of ERT data (non-unique solution) (LaBrecque et al., 1996), and (ii) to errors associated to the other mass balance terms. The water balance calculated between the DOY 231 and 236 is quite high and equal to -11.92 mm. We assume this difference is due to an underestimation of the rainfall occurring the DOY 232. Indeed, it was a huge intensive rain (13.5 mm in 12 min) that could be under-measured by the automatic tipping bucket rainfall gauge. This type of gauge usually underestimates the high rainfall by not considering the loss of water during the bucket rotation (Marsalek, 1981; Vasvári, 2005). Moreover, this stormy event may generated spatially highly variable precipitations. By comparing the precipitations given by 2 meteorological stations located at 1.3 km from each other, we observed for this rainy event a difference of precipitations of 4.2 mm.

3.2.2 Comparison between SWC measured by TDR and ERT

Figure 7 compares the average SWC obtained by TDR and by ERT at the four TDR depths for the rows and inter-rows measurements together (full markers). The correlation between the mean SWC determined by the two methods is very good ($R^2 = 0.98$). For the same time, we plotted the minimum and maximum SWC at each depth, for the two methods (unfilled markers). This illustrates the horizontal variability of TDR and ERT SWC measurements. At 10 cm depth, the difference between the maximum and minimum of SWC at each depth and time ranged from $0.0234 \text{ cm}^3 \text{ cm}^{-3}$ to $0.0925 \text{ cm}^3 \text{ cm}^{-3}$ for TDR measurements and from

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



0.1142 cm³ cm⁻³ to 0.1661 cm³ cm⁻³ for ERT measurements. At 125 cm the deviation was smaller and never exceeded 0.0221 cm³ cm⁻³ for both methods. The maximum difference of SWC with TDR are in the same range as the maximum SWC difference obtained with neutron probes by Hupet and Vanclooster (2005). The higher deviation for ERT measurements than for TDR measurements can be explained by the higher spatial resolution of ERT measurements and thus by the discrimination of more SWC heterogeneities, especially visible in the first soil horizon. It establishes that ERT is appropriate to quantify the SWC spatial variability.

The evolution of SWC at four depths during the experimental time is represented in Fig. 8. The shaded envelopes encompass the spatial variability associated to the two TDR probes of each depth for the row or inter-row areas, excepted at 125 cm depth where only one probe was present for the row area and one for the inter-row area. For each depth and area, we plotted the SWC measurements obtained by ERT.

For each soil layer and for the same times, the agreement between TDR and ERT was generally good, especially for the three upper depths. At 125 cm depth, ERT measurements were slightly different, with a maximum of 0.011 cm³ cm⁻³, considering one standard deviation. This difference is smaller than the error associated to the TDR calibration and is similar to the error associated to the pedoelectrical relationship. Brunet et al. (2010) compared the water content and water content deficit obtained from ERT with local measurements made with TDR at ten different times. Their comparison showed that ERT and TDR water content values globally exhibit the same temporal pattern, but with sometimes absolute differences up to of 0.05 cm³ cm⁻³, which is acceptable but higher than what we observed in our study.

With the Figs. 6–8, we demonstrated that the ERT methodology reasonably estimate SWC at the field scale and give comparable results as TDR that is considered by many authors as an accurate way to measure SWC (Huisman et al., 2001; Robinson et al., 2003; Walker et al., 2004).

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.3 Processes inducing SWC distribution

3.3.1 SWC spatial variability

Figure 9 shows three-dimensional SWC distributions for the first day of ERT measurement (DOY 225). The irregular and non-horizontal isosurfaces illustrate the heterogeneity of the 3-D SWC distribution. The maize rows, perpendicular to the x-axis at 0.6 m and 1.35 m, seem to influence the drying pattern as suggested by Hupet and Vanclooster (2005). To quantify the maize rows effect on the spatial variability of SWC, we realized 2-D maps of the SWC coefficient of variation (CV) following the maize rows (y direction, visible on x-axis) and perpendicular to the maize rows (x direction, visible on y-axis) (Fig. 10).

The distribution of the CV is similar for the nine measurement times. The CV is higher in the first soil horizon for the x and y directions, where SWC was comprized between 0.123 and 0.328 cm³ cm⁻³ (Fig. 8). But the CV is lower on the x-axis (in the maize rows direction) for the whole soil profile. We then assume that the SWC is relatively homogeneous within the row. At the opposite, the CV on the y-axis, considering alternation of maize rows and inter-rows, is relatively high with a decrease of CV with depth. In the following sections, we will partly explain the processes that are acting in the SWC distribution in this maize field.

3.3.2 SWC evolution during the late growing season of maize

For sake of clarity, we realized 2-D maps by calculating the average of SWC distributions along y-axis (visible on the x-axis), considering the relatively low CV in that direction. We could then observe the maize row/inter-row effect on the y-average SWC distribution at 9 different dates (Fig. 11). We observed a contrast of SWC between row and inter-row areas along the whole experimental period. The soil was drier under maize rows and the difference between the middle of the row and the middle of the inter-row area at the same depth and time could reach 0.181 cm³ cm⁻³ in the first

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



soil horizon (at DOY 231), and never exceeded $0.09 \text{ cm}^3 \text{ cm}^{-3}$ in the third soil horizon. During the experimental period, the SWC decreased especially in the second and third soil horizon, especially under the maize rows, creating a specific drying pattern. At the end of experimental period, the drying pattern was influenced till the third soil horizon by the maize rows. Michot et al. (2003), Hupet and Vanclooster (2005) and Srayeddin and Doussan (2009) observed similar patterns in maize field due to root water uptake (Michot et al., 2001).

The drying patterns evolve with time by drying deeper soil layers. However, the general shape remains the same, with dry zones under the maize rows and at the soil surface; even at measurement times following consequent rainfall events (for instance DOY 236, 252, 261). As show in the next section, we suggest that the precipitations are not sufficient to change the SWC pattern created by root water uptake.

The root impact profiles realized at three different dates are shown in Fig. 12. The number of roots impacts increased with time but the distribution in the profile stayed similar. The roots impacts were denser in the upper soil layer with a decrease at the plough pan layer mainly visible in the two first roots profiles. The roots were more presents under the maize rows than between the maize rows. Li et al. (2002) observed that in the well-watered soil profile, it is the spatial distribution of the roots that mainly determines the typical pattern of root extraction, in addition to the fact that the roots near the plant base are more effective than those farther away. At DOY 225, 239 and 261, the depth of the patterns of SWC (Fig. 11a, f, i) affected by maize rows reaches and maybe exceeds the maximum measurement depth of root distribution (1 m) (Fig. 12). Between DOY 225 and 239, the SWC distribution evolves to a deeper drying pattern under maize rows. Similarly, between DOY 225 and 239, the roots impacts increased on the whole soil profile. Between DOY 239 and 261, the roots distribution seems similar but with a number of roots impact higher at each depth for the DOY 261. The SWC drying pattern has the same shape for the two dates but is a little more pronounced for DOY 261 and goes deeper.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Between the first (DOY 225) and the last (DOY 261) ERT measurement time, SWC decreased in the whole soil profile, except in the 20 first centimeters (Fig. 13). The precipitations were not sufficient to compensate crop transpiration and the water stock decreased from 448 mm to 424 mm as observed in the water mass balance (Fig. 6).

The increase of SWC at the surface was due to a rainfall event occurring at the end of the growing season. In the second soil horizon, we observed a decrease of SWC with depth going from $0.015 \text{ cm}^3 \text{ cm}^{-3}$ to $0.038 \text{ cm}^3 \text{ cm}^{-3}$. At the interface between the second and third soil horizon, the depletion curve was discontinuous and then relatively constant at around $0.02 \text{ cm}^3 \text{ cm}^{-3}$ in the third soil horizon. As observed by Garré et al. (2011) and Vandoorne et al. (2012) the water depletion does not reflect the uptake and root distributions.

3.3.3 Effect of root water uptake and precipitation on the SWC changes

To determine the effect of precipitations and root water uptake on the SWC distribution, we investigated the SWC change between four days and their following ERT measurement time in 2-D (Fig. 14). We quantified the SWC change during two small periods (2 and 4 days) with negligible rainfall ($P = 1.3 \text{ mm}$) and two longer periods (9 days each) with consequent rain events ($P = 16.7 \text{ mm}$ and 10.1 mm , respectively).

During the two dry periods, we observed with ERT a slight decrease of SWC in the soil profile. Between DOY 237 and 239 (Fig. 14b), the SWC depletion was mainly located in the first soil horizon. Between DOY 239 and 243 (Fig. 14c), the SWC depletion took place mainly under the inter-rows in the two upper soil horizons, at the opposite of Michot et al. (2003) who observed a decrease of SWC under the maize rows. Considering the SWC distribution patterns and the SWC changes, we assume that the decrease of SWC occurred first under the maize rows and then in the deeper zones and in the inter-row areas. Li et al. (2002) suggested that low soil hydraulic conductivity in the soil near the plant base, due to low SWC, is the initial cause for downward and lateral shifting of the root uptake patterns. During these two dry periods, the SWC decrease was low and slightly visible with ERT. With TDR we cannot observe significant

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



decrease of SWC. The considered periods are too small to observe large decrease of SWC and the error linked to the TDR is in the same order of magnitude as the SWC decrease.

When we plot SWC changes of rainy periods (DOY 243–252 and DOY 252–261), we observe that only the first soil horizon is affected by the precipitations (Fig. 14e, f) and that the ERT soil water storage is decreasing during these periods as shown by the water mass balance (Fig. 6). A decrease of SWC took place in the inter-row area of the first soil horizon and everywhere in the second and third soil horizons. At the opposite, the increase of SWC is mainly located in the first soil horizon and under the maize rows, where the SWC was the lowest before the rain (Fig. 11). Michot et al. (2003) mentioned that selective infiltration occur under the maize plants due to preferential directions of water flux and the role of the aerial part of maize plant to catch water, create stem flow and promote infiltration under the maize plant. We used the TDR measurements to confirm this hypothesis. When we discriminate TDR probes between row and inter-row, they show a quick increase of SWC under the maize rows at 10 cm-depth just a few minutes after rainfall event start. When the precipitations are sufficient, the row-SWC at 10 cm will reach and eventually exceed the level of SWC of the inter-row. When the rain stopped, SWC below the maize row of the first depth decreases again, while no increase is observed in other locations. Therefore, this decrease reflects the impact of RWU rather than lateral soil water redistribution. With ERT, we can only see the change of SWC between our measurement times. Although 5 and 3 days passed after the rainfall event, respectively for the first and second long periods, the SWC increase zone is still located below the maize row, which confirms that rainfall are not sufficient to change the drying pattern and that lateral redistribution from the maize rows to the inter-rows hardly occurred in this maize field during our measurement time.

With TDR measurements, we can follow the dynamic of SWC but the spatial distribution is limited and the small changes of SWC are not really visible. It is therefore advantageous to combine TDR and ERT measurements to monitor the SWC distribution at the field scale.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



By investigating the effect of root water uptake and precipitation on the dynamics of SWC distribution, we suggest that both are influencing the SWC variability. Root water uptake, by creating drying patterns is generating variability. At the opposite, precipitations increase the SWC under the maize rows, where the soil is the driest, by preferential infiltration. This preferential infiltration tends to homogenize the SWC, as showed by the decrease of CV in the first soil horizon for the two days preceded by consequent rainfall (DOY 252 and 261) (Fig. 10p, r).

4 Conclusions

This study was conducted (i) to validate our ERT methodology to determine the SWC distribution in 3-D at the plot scale and (ii) to investigate how precipitations and root water uptake affect the SWC dynamics at this scale by combining ERT and TDR measurements. For that, 14 TDR probes were horizontally inserted at 4 depths (10 cm, 30 cm, 70 cm and 125 cm) and an ERT setup comprising 76 surfaces electrodes and 56 in-depth electrodes was installed. The TDR probes gave us hourly measurements of SWC and with the ERT setup, we obtained the SWC in 3-D on a 5 cm side grid at 9 dates during the experimental time. The upper boundary conditions were monitored with a meteorological station located close to the experimental plot and the drainage was estimated using deep tensiometers.

The validation of ERT to derive the 3-D distribution of SWC was performed using a global mass balance method and a comparison between TDR and ERT measurements. The water stock given by ERT measurements provided a good estimate of the water storage during the experimental time (DOY 225 till DOY 261), except for one time (between DOY 231 and 237) where a stormy rain could have been underestimated. We observed increases of water stock depending on the intensity and duration of the rain and a general decrease due to ETC during the experimental period. The water stock quantification for TDR and ERT highlighted the improvement expected with ERT due to its better spatial resolution as compared to TDR measurements.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



By comparing averaged SWC measured by TDR and by ERT at four depths, we demonstrated the accuracy of ERT for estimating the mean ($R^2 = 0.98$) and the variability of the SWC. We observed that the SWC spatial variability is higher in the first soil horizon where the soil is drier and roots more present than in the two other soil horizons. We observed a higher CV of SWC distribution in the direction perpendicular (visible on y-axis) to the row than parallel (visible on x-axis). We confirmed that the SWC distribution is influenced by the maize row pattern and roots development.

Between DOY 225 and DOY 261 (ERT experimental time), a decrease of the soil water storage was observed due to rainfall deficit. The global SWC mainly decreased in the deeper soil layers, where the soil was initially wetter. In the second and third soil horizons, the SWC decrease was about $0.038 \text{ cm}^3 \text{ cm}^{-3}$ and $0.02 \text{ cm}^3 \text{ cm}^{-3}$, respectively. As already observed by Garré et al. (2011) and Vandoorne et al. (2012), the shape of the soil water depletion profile does not reflect the root distribution.

During dry periods, the SWC decreased mainly in the first and second soil horizon, mainly in the inter-rows area. At the beginning of ERT measurement time (DOY 225), the soil was already relatively dry under the maize rows in the first soil horizon. As mentioned by Li et al. (2002), the hydraulic conductivity becomes lower when the soil dries and induces lateral and downward root water uptake. At the opposite, the precipitations and the preferential infiltration increase the SWC mainly under the maize rows in the first soil horizon, where the soil is the driest. But, the local increase of SWC was not sufficient to modify the general row/inter-rows pattern which remains visible along the whole period. Lateral soil water redistribution from the maize rows to the inter-rows was hardly visible during the season. ERT allows observing small change in SWC between two dates with a good spatial resolution and, with TDR, we can follow the evolution of SWC with a good temporal resolution. We conclude that combination of TDR and ERT provide an excellent tool for investigating SWC dynamics at the plot scale.

Further studies should be realized on the impact of root water uptake and precipitations on the dynamics of SWC distribution. This could be achieved by more regular ERT SWC measurements considering the meteorological conditions. Coupled with

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



better measurements of boundary fluxes, as plant transpiration with sap flow for instance, it could help to characterize with more accuracy the processes generating and destroying SWC heterogeneity, and thus improve SWC distribution predictions.

Acknowledgements. This study was done with the financial support of a Research Grant of the Fund for Scientific Research (Belgium) (F.N.R.S./FRIA). The authors acknowledge the technicians for their assistance during the field preparation and monitoring. Special thanks to Sarah Garré for her advices and our discussions.

References

- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage FAO, Rome, 1998.
- Archie, G. E.: The electrical resistivity log as an aid in determining some reservoir characteristics, T. AIME, 146, 54–67, 1942.
- Bing, Z. and Greenhalgh, S. A.: Cross-hole resistivity tomography using different electrode configurations, Geophys. Prospect., 48, 887–912, 2000.
- Binley, A., Cassiani, G., Middleton, R., and Winship, P.: Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging, J. Hydrol., 267, 147–159, 2002.
- Brunet, P., Clément, R., and Bouvier, C.: Monitoring soil water content and deficit using electrical resistivity tomography (ERT) – a case study in the Cevennes area, France, J. Hydrol., 380, 146–153, 2010.
- Cassiani, G., Bruno, V., Villa, A., Fusi, N., and Binley, A. M.: A saline trace test monitored via time-lapse surface electrical resistivity tomography, J. Appl. Geophys., 59, 244–259, 2006.
- Clothier, B. E. and Green, S. R.: Rootzone processes and the efficient use of irrigation water, Agr. Water Manage., 25, 1–12, 1994.
- Coelho, E. F. and Or, D.: Root distribution and water uptake patterns of corn under surface and subsurface drip irrigation, Plant Soil, 206, 123–136, 1999.
- Devitt, D. A. and Smith, S. D.: Root channel macropores enhance downward movement of water in a Mojave Desert ecosystem, J. Arid Environ., 50, 99–108, 2002.
- European Soil Bureau Network: Soil Atlas of Europe, edited by: Jones, A., Montanarella, L., and Jones, R., European Commission, Office for Official Publications of the European Communities, 2995 Luxembourg, 128 pp., 2005.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



▶

[Back](#)

Close

Full Screen / Esc

[Printer-friendly Version](#)

Interactive Discussion



- Flury, M., Leuenberger, J., Studer, B., and Flühler, H.: Transport of anions and herbicides in a loamy and a sandy field soil, *Water Resour. Res.*, 31, 823–836, 1995.
- Friedel, S.: Resolution, stability and efficiency of resistivity tomography estimated from a generalized inverse approach, *Geophys. J. Int.*, 153, 305–316, 2003.
- 5 Garré, S., Koestel, J., Günther, T., Javaux, M., Vanderborght, J., and Vereecken, H.: Comparison of heterogeneous transport processes observed with electrical resistivity tomography in two soils, *Vadose Zone J.*, 9, 336–349, 2010.
- Garré, S., Javaux, M., Vanderborght, J., Pagès, L., and Vereecken, H.: Three-dimensional electrical resistivity tomography to monitor root zone water dynamics, *Vadose Zone J.*, 10, 412–424, 2011.
- 10 Gish, T. J., Gimenez, D., and Rawls, W. J.: Impact of roots on ground water quality, *Plant Soil*, 200, 47–54, 1998.
- Green, S. R., Kirkham, M. B., and Clothier, B. E.: Root uptake and transpiration: from measurements and models to sustainable irrigation, *Agr. Water Manage.*, 86, 165–176, 2006.
- 15 Günther, T., Rücker, C., and Spitzer, K.: Three-dimensional modelling and inversion of dc resistivity data incorporating topography – II. Inversion, *Geophys. J. Int.*, 166, 506–517, 2006.
- Heimovaara, T. J.: Design of triple-wire time domain reflectometry probes in practice and theory, *Soil Sci. Soc. Am. J.*, 57, 1410–1417, 1993.
- Huisman, J. A., Sperl, C., Bouten, W., and Verstraten, J. M.: Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar, *J. Hydrol.*, 245, 48–58, 2001.
- 20 Hupet, F. and Vanclooster, M.: Intraseasonal dynamics of soil moisture variability within a small agricultural maize cropped field, *J. Hydrol.*, 261, 86–101, 2002.
- Hupet, F. and Vanclooster, M.: Micro-variability of hydrological processes at the maize row scale: implications for soil water content measurements and evapotranspiration estimates, *J. Hydrol.*, 303, 247–270, 2005.
- 25 Hupet, F., Bogaert, P., and Vanclooster, M.: Quantifying the local-scale uncertainty of estimated actual evapotranspiration, *Hydrol. Process.*, 18, 3415–3434, 2004.
- Jacques, D., Mohanty, B., Timmerman, A., and Feyen, J.: Study of time dependency of factors affecting the spatial distribution of soil water content in a field-plot, *Phys. Chem. Earth Pt. B*, 30, 629–634, 2001.

- Kemna, A., Vanderborght, J., Kulesa, B., and Vereecken, H.: Imaging and characterisation of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models, *J. Hydrol.*, 267, 125–146, 2002.
- 5 Koestel, J., Kemna, A., Javaux, M., Binley, A., and Vereecken, H.: Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3-D ERT and TDR, *Water Resour. Res.*, 44, W12411, doi:10.1029/2007WR006755, 2008.
- Koestel, J., Vanderborght, J., Javaux, M., Kemna, A., Binley, A., and Vereecken, H.: Noninvasive 3-D transport characterization in a sandy soil using ERT: 2. Transport process inference, *Vadose Zone J.*, 8, 723–734, 2009a.
- 10 Koestel, J., Vanderborght, J., Javaux, M., Kemna, A., Binley, A., and Vereecken, H.: Noninvasive 3-D transport characterization in a sandy soil using ERT: 1. Investigating the validity of ERT-derived transport parameters, *Vadose Zone J.*, 8, 711–722, 2009b.
- Koumanov, K. S., Hopmans, J. W., and Schwankl, L. W.: Spatial and temporal distribution of root water uptake of an almond tree under microsprinkler irrigation, *Irrigation Sci.*, 24, 267–278, 2006.
- 15 LaBrecque, D. J. and Yang, X.: Difference inversion of ERT data: a fast inversion method for 3-D in situ monitoring, *J. Environ. Eng. Geoph.*, 6, 83–90, 2001.
- LaBrecque, D. J., Miletto, M., Daily, W., Ramirez, A., and Owen, E.: The effects of noise on Occam's inversion of resistivity tomography data, *Geophysics*, 61, 538–548, 1996.
- 20 Laloy, E., Javaux, M., Vanclooster, M., Roisin, C., and Biéders, C. L.: Electrical resistivity in a loamy soil: identification of the appropriate pedo-electrical model, *Vadose Zone J.*, 10, 1023–1033, 2011.
- Li, Y., Wallach, R., and Cohen, Y.: The role of soil hydraulic conductivity on the spatial and temporal variation of root water uptake in drip-irrigated corn, *Plant Soil*, 243, 131–142, 2002.
- 25 Mallants, D., Jacques, D., Vanclooster, M., Diels, J., and Feyen, J.: A stochastic approach to simulate water flow in a macroporous soil, *Geoderma*, 70, 299–324, 1996.
- Marsalek, J.: Calibration of the tipping-bucket raingage, *J. Hydrol.*, 53, 343–354, 1981.
- Merz, R., Blöschl, G., and Parajka, J.: Spatio-temporal variability of event runoff coefficients, *J. Hydrol.*, 331, 591–604, 2006.
- 30 Michot, D., Dorigny, A., and Benderitter, Y.: Mise en évidence par résistivité électrique des écoulements préférentiels et de l'assèchement par le maïs d'un CALCICOL de Beauce irrigué, *C. R. Acad. Sc. Paris, Série IIA*, 332, 29–36, 2001.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D., and Tabbagh, A.: Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography, *Water Resour. Res.*, 39, 1138, doi:10.1029/2002WR001581, 2003.
- 5 Minet, J.: High-Resolution Soil Moisture Mapping by a Proximal Ground Penetrating Radar: a Numerical, Laboratory and Field Evaluation, *Faculté d'Ingénierie Biologique, Agronomique et Environnementale, Université Catholique de Louvain, Louvain-la-Neuve (Belgium)*, 195 pp., 2011.
- 10 Mooney, S. J. and Morris, C.: Morphological approach to understanding preferential flow using image analysis with dye tracers and X-ray computed tomography, *Catena*, 73, 204–211, 2008.
- Norbiato, D., Borga, M., Merz, R., Blöschl, G., and Carton, A.: Controls on event runoff coefficients in the Eastern Italian Alps, *J. Hydrol.*, 375, 312–325, 2009.
- 15 Oberdörster, C., Vanderborght, J., Kemna, A., and Vereecken, H.: Investigating preferential flow processes in a forest soil using time domain reflectometry and electrical resistivity tomography, *Vadose Zone J.*, 9, 350–361, 2010.
- Oliveira, R. S., Bezerra, L., Davidson, E. A., Pinto, F., Klink, C. A., Nepstad, D. C., and Moreira, A.: Deep root function in soil water dynamics in cerrado savannas of Central Brazil, *Funct. Ecol.*, 19, 574–581, 2005.
- 20 Revil, A., Cathles, L. M., Losh, S., and Nunn, J. A.: Electrical conductivity in shaly sands with geophysical applications, *J. Geophys. Res.-Sol. Ea.*, 103, 23925–23936, 1998.
- Rhoades, J. D., Manteghi, N. A., Shouse, P. J., and Alves, W. J.: Soil electrical conductivity and soil salinity: new formulations and calibrations, *Soil Sci. Soc. Am. J.*, 53, 433–439, 1989.
- 25 Robinson, D. A., Jones, S. B., Wraith, J. M., Or, D., and Friedman, S. P.: A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry, *Vadose Zone J.*, 2, 444–475, 2003.
- Rücker, C. and Günther, T.: The simulation of finite ERT electrodes using the complete electrode model, *Geophysics*, 76, 227–238, 2011.
- 30 Rücker, C., Günther, T., and Spitzer, K.: Three-dimensional modelling and inversion of dc resistivity data incorporating topography – I. Modelling, *Geophys. J. Int.*, 166, 495–505, 2006.
- Samouelian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G.: Electrical resistivity survey in soil science: a review, *Soil Till. Res.*, 83, 173–193, 2005.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Schwartz, B. F., Schreiber, M. E., and Yan, T.: Quantifying field-scale soil moisture using electrical resistivity imaging, *J. Hydrol.*, 362, 234–246, 2008.
- Sharp, R. E. and Davies, W. J.: Root growth and water uptake by maize plants in drying soil, *J. Exp. Bot.*, 36, 1441–1456, 1985.
- 5 Slater, L., Binley, A. M., Daily, W., and Johnson, R.: Cross-hole electrical imaging of a controlled saline tracer injection, *J. Appl. Geophys.*, 44, 85–102, 2000.
- Slater, L., Binley, A., Versteeg, R., Cassiani, G., Birken, R., and Sandberg, S.: A 3-D ERT study of solute transport in a large experimental tank, *J. Appl. Geophys.*, 49, 211–229, 2002.
- 10 Srayeddin, I. and Doussan, C.: Estimation of the spatial variability of root water uptake of maize and sorghum at the field scale by electrical resistivity tomography, *Plant Soil*, 319, 185–207, 2009.
- Tardieu, F.: Analysis of the spatial variability of maize root density – II. Distances between roots, *Plant Soil*, 107, 267–272, 1988.
- Teuling, A. J. and Troch, P. A.: Improved understanding of soil moisture variability dynamics, *Geophys. Res. Lett.*, 32, 1–4, 2005.
- 15 Topp, G. C., Davis, J. L., and Annan, A. P.: Electromagnetic determination of soil-water content – measurements in coaxial transmission-lines, *Water Resour. Res.*, 16, 574–582, 1980.
- Udphuay, S., Günther, T., Everett, M. E., Warden, R. R., and Briaud, J. L.: Three-dimensional resistivity tomography in extreme coastal terrain amidst dense cultural signals: application to cliff stability assessment at the historic D-Day site, *Geophys. J. Int.*, 185, 201–220, 2011.
- 20 van Genuchten, M. T.: Closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, 44, 892–898, 1980.
- Vanderborght, J., Kemna, A., Hardelauf, H., and Vereecken, H.: Potential of electrical resistivity tomography to infer aquifer transport characteristics from tracer studies: a synthetic case study, *Water Resour. Res.*, 41, 1–23, 2005.
- 25 Vandoorne, B., Beff, L., Lutts, S., and Javaux, M.: Root water uptake dynamics of *Cichorium intybus* var. *sativum* under water-limited conditions, *Vadose Zone J.*, in press, 2012.
- Vasvári, V.: Calibration of tipping bucket rain gauges in the Graz urban research area, *Atmos. Res.*, 77, 18–28, 2005.
- 30 Walker, J. P., Willgoose, G. R., and Kalma, J. D.: In situ measurement of soil moisture: a comparison of techniques, *J. Hydrol.*, 293, 85–99, 2004.
- Waxman, M. H. and Smits, L. J. M.: Electrical conductivities in oil-bearing shaly sands, *Soc. Petrol. Eng. J.*, 243, 107–122, 1968.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Werban, U., Al Hagrey, S. A., and Rabbel, W.: Monitoring of root-zone water content in the laboratory by 2-D geoelectrical tomography, *J. Plant Nutr. Soil Sc.*, 171, 927–935, 2008.
- Western, A. W., Grayson, R. B., Blöschl, G., and Wilson, D. J.: Spatial variability of soil moisture and its implications for scaling, in: *Scaling Methods in Soil Physics*, edited by: Pachepsky, Y., Radcliffe, D. E., and Selim, H. M., CRC Press, Florida, 119–142, 2003.
- Weynants, M.: *Linking Soil Hydraulic Properties to Structure Indicators: Experiments and Modelling*, Earth and Life Institute – Environmental Sciences, Université Catholique de Louvain, Louvain-la-Neuve (Belgium), 2011.

HESSD

9, 8535–8578, 2012

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil water content monitoring in a maize field using ERT

L. Beff et al.

Table 1. Textural and hydraulic properties for each soil horizon. S , L and C represent respectively the percentage of Sand, Loam and Clay. BD is the soil bulk density. θ_r and θ_s are respectively the saturated and the residual SWC. α , n and l are Van Genuchten hydraulic parameters.

Soil Horizon	S (%)	L (%)	C (%)	BD (gcm ⁻³)	pH	θ_s (cm ³ cm ⁻³)	θ_r (cm ³ cm ⁻³)	K_s (cmmin ⁻¹)	α (cm ⁻¹)	n (–)	l (–)
Ap	3	76	21	1.4208	7.1	0.4422	0.145	0.0785	0.0352	1.2648	3.9544
Bt1	1	67	32	1.4399	7.7	0.4451	0.2	0.1142	0.106	1.219	1.2059
Bt2	1	74	25	1.4957	7.7	0.4396	0.0284	0.9972	0.0941	1.1	1.7336

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


**Soil water content
monitoring in a maize
field using ERT**

L. Beff et al.

Table 2. Parameters for the simplified Waxman and Smits model and rmse for each of the three soil horizons.

Horizon	a (Sm^{-1})	b (Sm^{-1})	c (–)	RMSE ($\text{cm}^3 \text{cm}^{-3}$)
Ap1	0.2999	0.006	2	0.0242
Bt1	0.6001	0.005	2.7	0.0195
Bt2	9.0012	0.001	5.4	0.0105

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



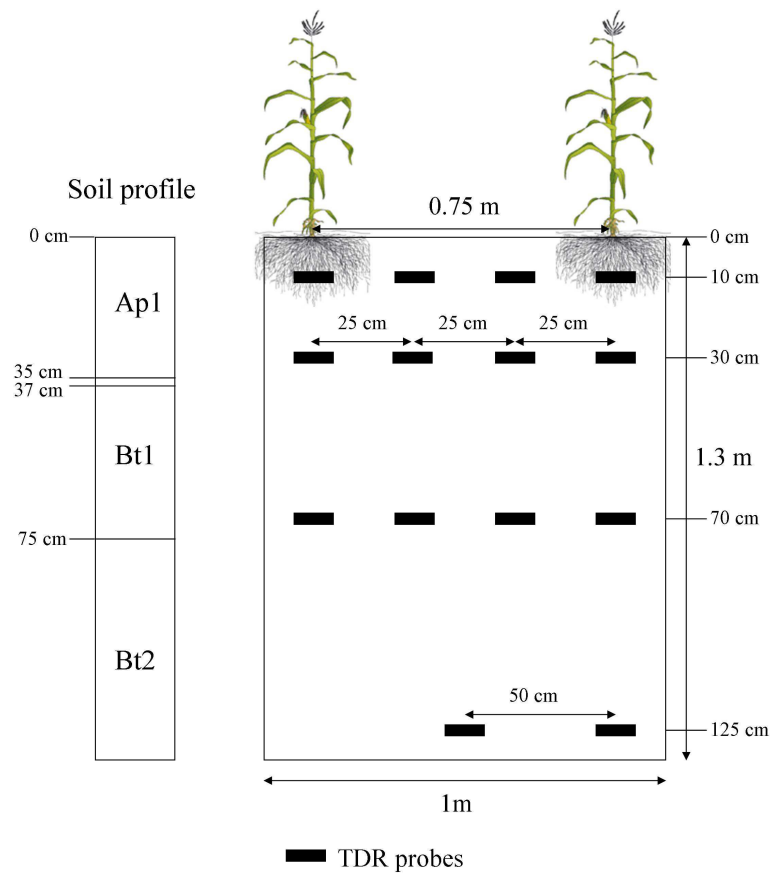


Fig. 1. Depth of the soil horizons (Ap1, plough sole, Bt1 and Bt2) and position of TDR probes.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

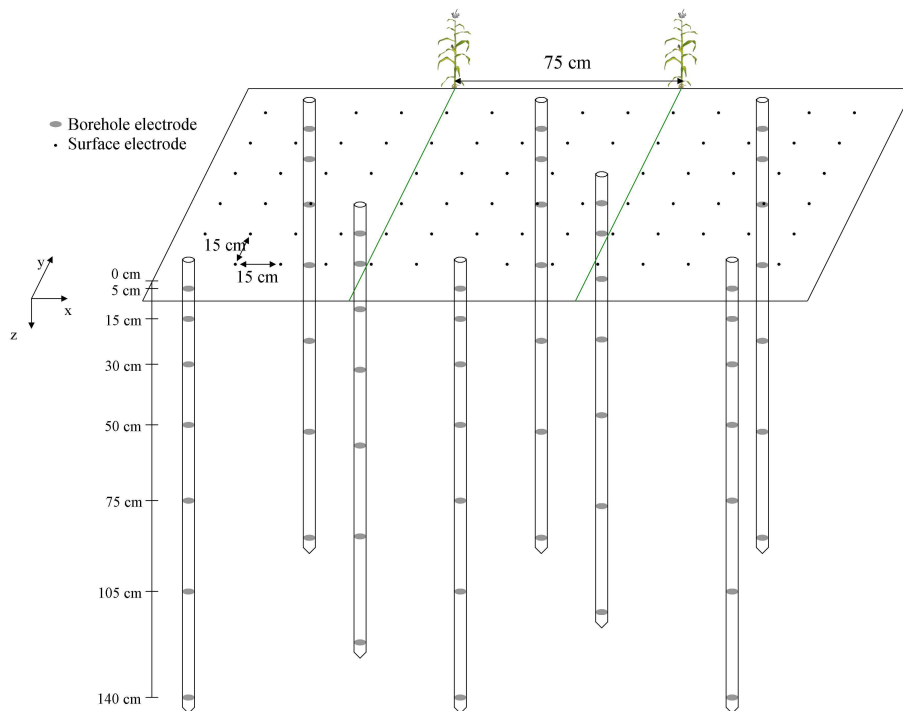


Fig. 3. Scheme of the ERT electrodes positions. The tubes with black rings represent the PVC sticks with the ring electrodes; the black dots represent the surface electrodes. The green lines correspond to the maize rows.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



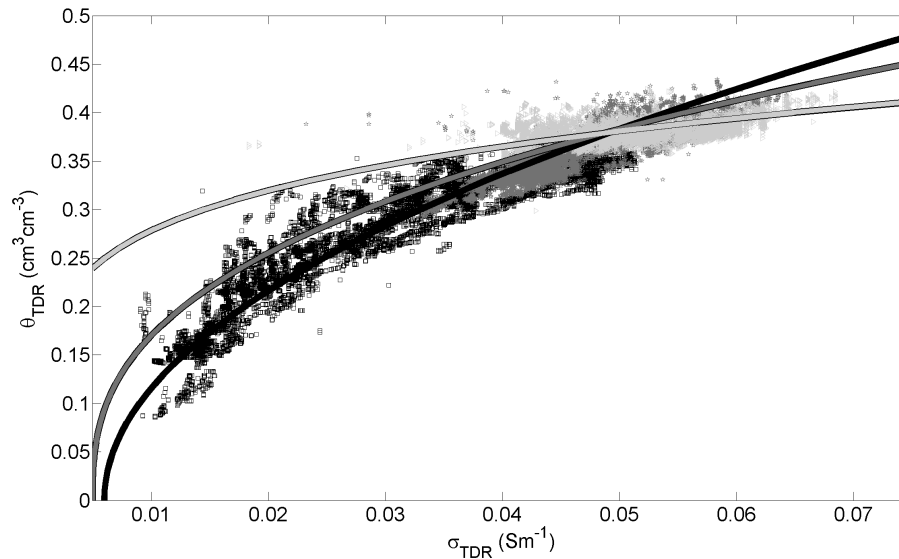


Fig. 4. σ_{TDR} and SWC for TDR measurements realized in the three soil horizons in 2010. The black squares are for the Ap1 horizon, the grey stars for the Bt1 horizon, and the light grey triangles for the Bt2 horizon. The curves represent the simplified Waxman and Smits (1968) model that fits the $\sigma_{\text{TDR}} - \theta_{\text{TDR}}$ couples (black for Ap1, grey for Bt1 and light grey for Bt2).

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



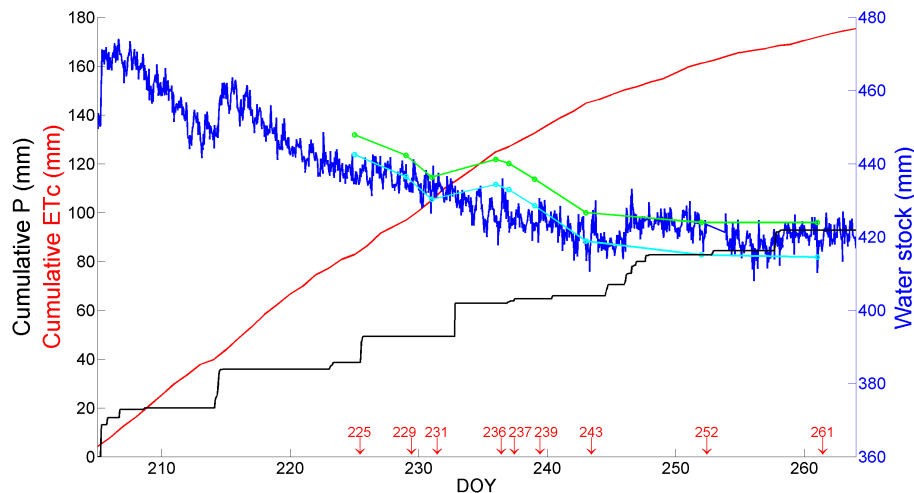


Fig. 5. Precipitations, crop evapotranspiration and water storage during the measurement time. Cumulative P (mm) (black), cumulative ETC (mm) (red), TDR water stock evolution (blue), ERT water stock (mm) (green with circles) and water stock considering ERT SWC at 4 depths and integrating the SWC as for TDR water stock (mm) (cyan circle). Red arrows represent the ERT measurement days.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



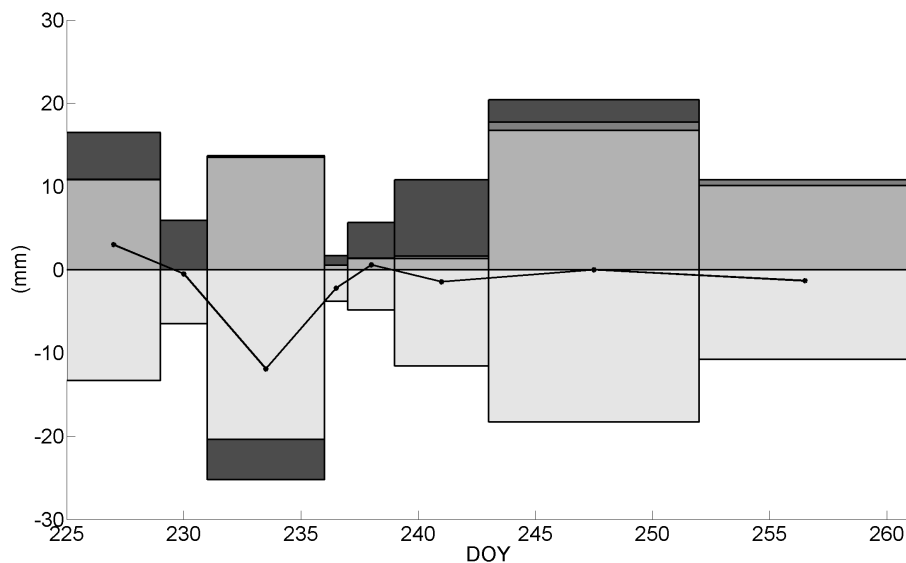


Fig. 6. Water balance between the nine ERT measurement times calculated with Eq. (11). Input includes precipitations (mm) (light-middle grey), capillary rise (mm) (middle grey), the output is the ETC (mm) (light grey). The water stock variation (mm) (dark grey) is positive when SWC decrease and negative for increase of SWC. The black line corresponds to the difference between the input and stock change and the output.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



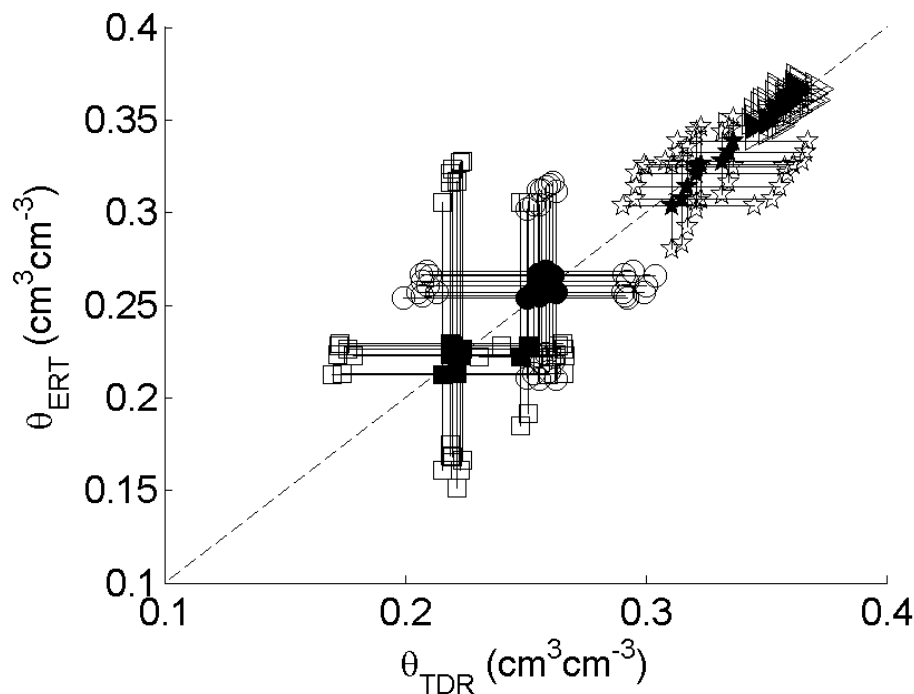


Fig. 7. Mean SWC measured by TDR and ERT at the 4 TDR measurement depths. The filled markers correspond to the mean SWC and the unfilled markers to the minimum and maximum SWC for each ERT measurement time for the same depths. The squares are for 10 cm depth, the circles for 30 cm depth, the stars for 70 cm depth and the triangles for 125 cm depth.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil water content monitoring in a maize field using ERT

L. Beff et al.

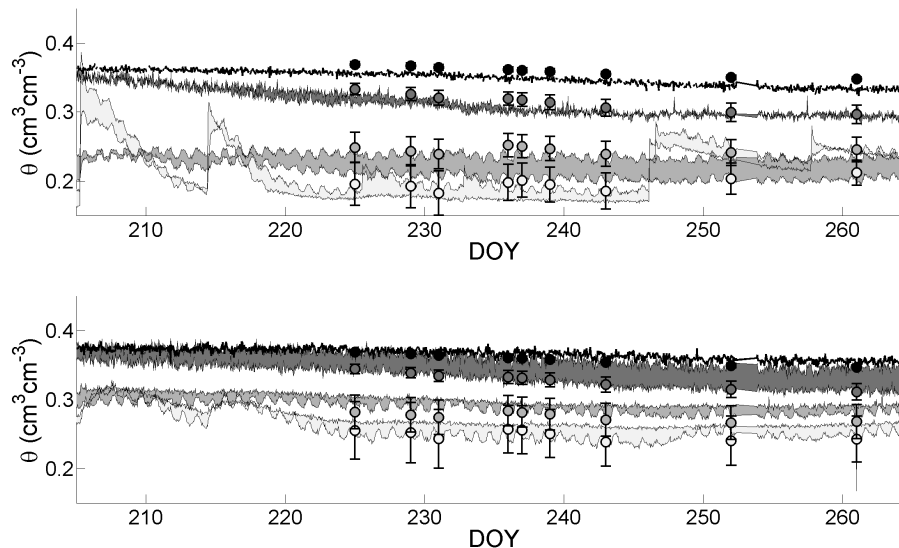


Fig. 8. Evolution of SWC at the four TDR measurement depths. The filled areas correspond to the SWC range based on two probes measurements in the row area **(a)** or in the inter-row area **(b)**. At 125 cm depth, only one probe was situated in the row area and one in the inter-row area. The circles are the ERT measurements at the same depth and at the corresponding time and the bar are one standard deviation for the corresponding ERT measurements. Light grey circles and filled areas are for 10 cm, middle grey for 30 cm, dark grey for 70 cm, and black for 125 cm.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

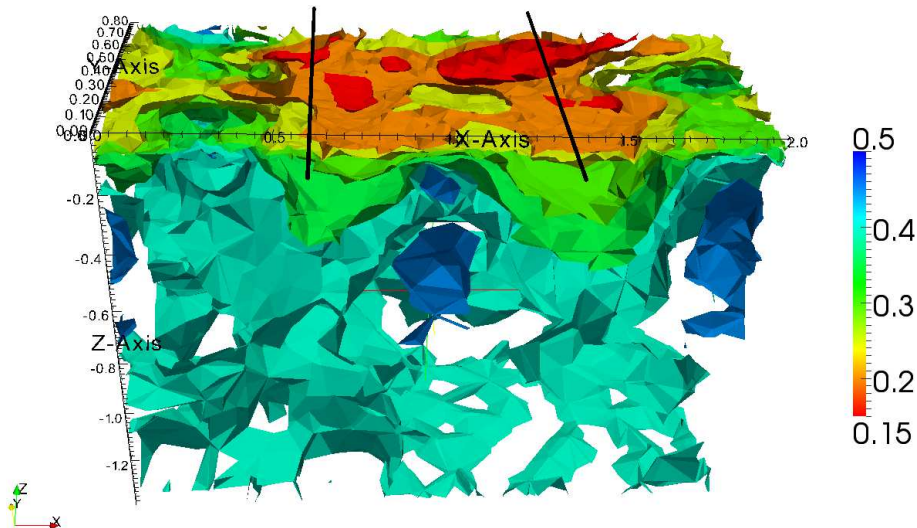



Fig. 9. Three-dimensional volumetric soil water content for the ERT experimental plot for the first ERT measurement times. The surfaces are isosurfaces of equal water content. The isosurfaces represent the volumetric soil water content at 0.15 ($\text{cm}^3 \text{cm}^{-3}$), 0.2 ($\text{cm}^3 \text{cm}^{-3}$), 0.25 ($\text{cm}^3 \text{cm}^{-3}$), 0.3 ($\text{cm}^3 \text{cm}^{-3}$), 0.35 ($\text{cm}^3 \text{cm}^{-3}$), 0.4 ($\text{cm}^3 \text{cm}^{-3}$), 0.45 ($\text{cm}^3 \text{cm}^{-3}$), and 0.5 ($\text{cm}^3 \text{cm}^{-3}$).

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil water content monitoring in a maize field using ERT

L. Beff et al.

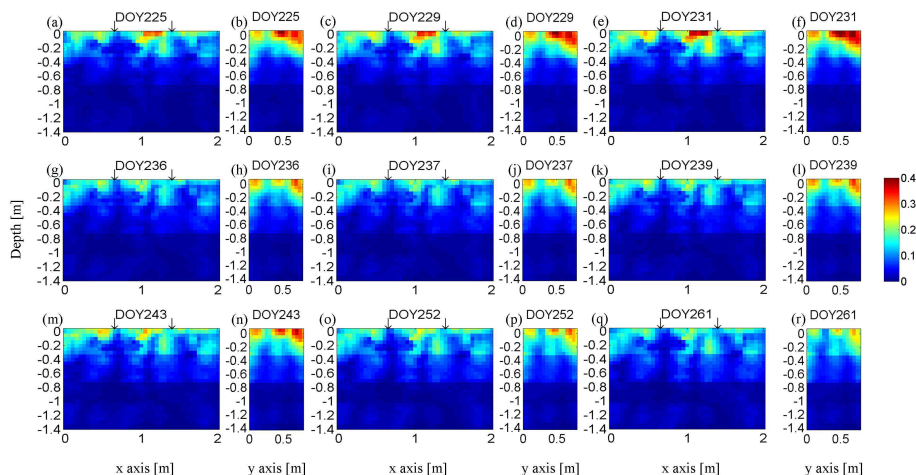


Fig. 10. SWC coefficient of variation for the nine ERT measurement times on the x-axis (**a, c, e, g, i, k, m, o, q**) and on the y-axis (**b, d, f, h, j, l, n, p, r**). The measurement day (DOY) is written above each subfigure. The arrows on the x-axis figures represent the maize rows positions. The colored scale corresponds to the coefficient of variation.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Soil water content monitoring in a maize field using ERT

L. Beff et al.

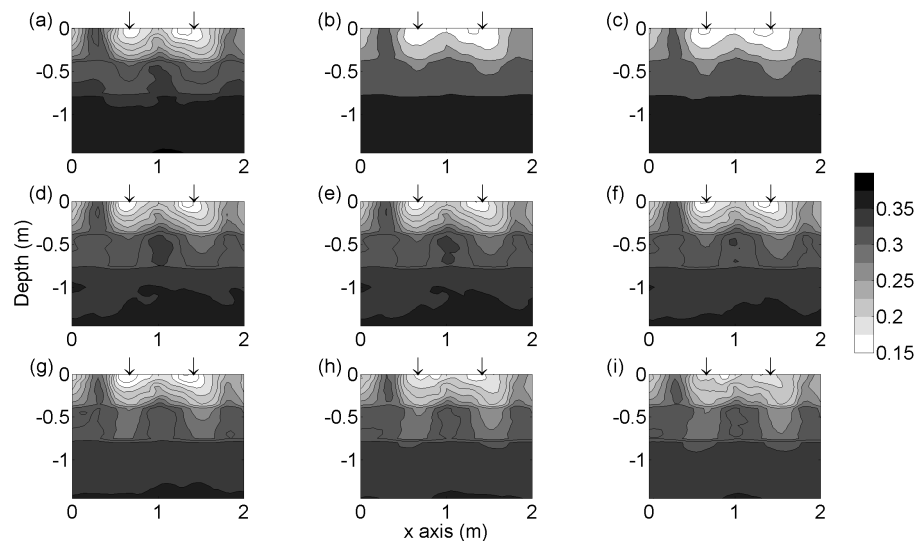


Fig. 11. Two-dimensional SWC distribution obtained by ERT at DOY 225 **(a)**, DOY 229 **(b)**, DOY 231 **(c)**, DOY 236 **(d)**, DOY 237 **(e)**, (DOY 239 **(f)**, DOY 243 **(g)**, DOY 252 **(h)**, DOY 261 **(i)**. The scale is the SWC ($\text{cm}^3 \text{cm}^{-3}$). The arrows indicate the Maize rows position.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Soil water content monitoring in a maize field using ERT

L. Beff et al.

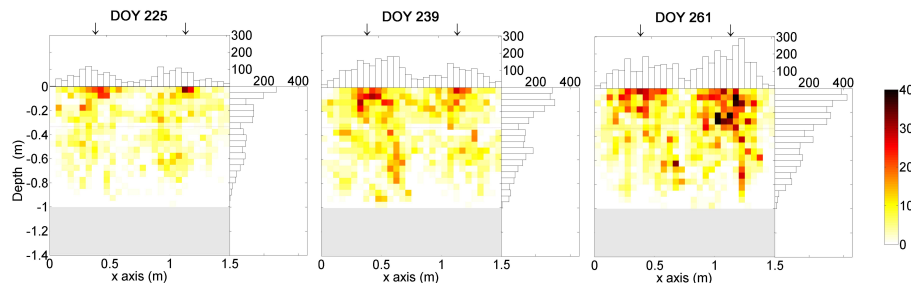


Fig. 12. Roots profiles obtained by Tardieu's method. The colored squares correspond to the number of root impacts, resulting in a 2-D distribution of roots. The colorscale represents the number of root impacts. The horizontal and vertical histograms corresponds to the number of roots impacts in 5 cm by 5 cm squares in the x and y directions, respectively. It helps to compare the number of impacts in the rows and inter-rows area and for the different depths. The grey area delimited the zone without measurements. The arrows indicate the maize rows position.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



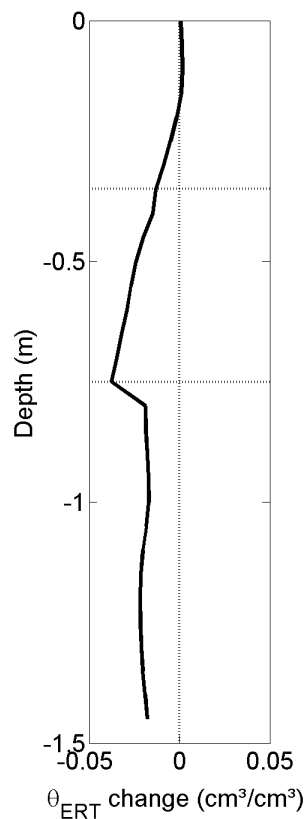


Fig. 13. SWC change for the whole soil profile between the first day of ERT measurement (DOY 225) and the last day (DOY 261). Negatives values means a decrease of SWC during the experimental time; positives values means an increase of SWC. The vertical dotted line is the limit between increase and decrease of SWC. The horizontal dotted lines correspond to the limits of the soil horizons.

Soil water content monitoring in a maize field using ERT

L. Beff et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Soil water content monitoring in a maize field using ERT

L. Beff et al.

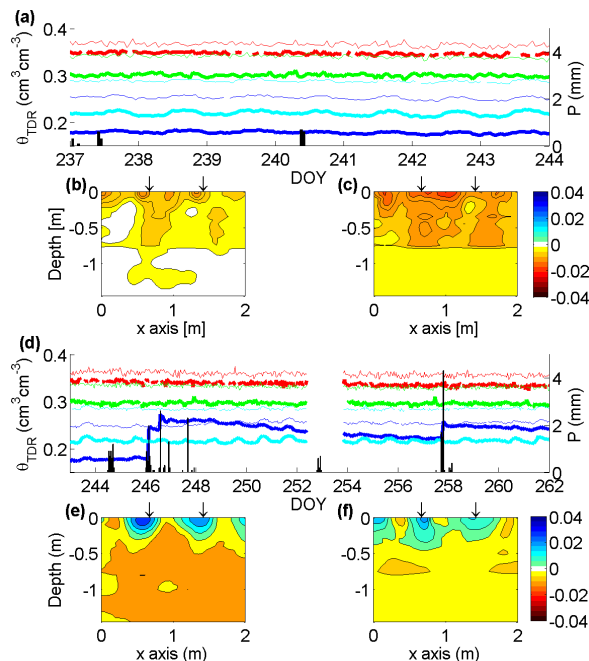


Fig. 14. TDR SWC content evolution during **(a)** two dry periods (DOY 237–239 and DOY 239–243) and **(d)** two wet periods (DOY 243–252 and DOY 252–261). The bold lines correspond to the Maize row TDR measurements and the thin lines to inter-rows measurements. Blue is for 10 cm depth, cyan for 30 cm depth, green for 70 cm depth and red for 125 cm depth. ERT SWC differences between two consecutive measurements times during dry **(b)** (DOY 237–239) and **(c)** (DOY 239–243)) and wet **(e)** (DOY 243–252) and **(f)** (DOY 252–261)) periods. The color scale corresponds to the soil water content changes ($\text{cm}^3 \text{cm}^{-3}$). Negatives values mean a decrease of SWC and the positives values mean an increase of SWC. The arrows indicate the maize rows position.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)