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Measuring areal soil moisture distribution with the TDR method

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ABSTRACT

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Time domain reflectometry (TDR) was used for measuring surface (0–10 cm) soil moisture content distribution of a field plot 6 m × 10 m in size. Within a regular grid, 273 points were measured by TDR and sampled for gravimetric (GM) moisture content determination, after harvest of a barley crop. Soil moisture content values were proven to be trended. The areal distributions of soil moisture contents were analyzed by semivariograms. The areal pattern of TDR moisture content values, but not of the gravimetric data, reflected the effect of the vehicle traffic during the harvest on the sample plot. The significant statistical difference found between the original TDR and GM moisture content values was attributed to the soil bulk density pattern existing on the study plot. Semivariograms of the detrended residuals show isotropy and no spatial structure. The standard error of the mean as a function of sample size was calculated for the detrended data. The study illustrates the good in situ applicability of the TDR method and examples how soil bulk density might appear in field measured TDR soil moisture content.

INTRODUCTION

Time domain reflectometry (TDR) is a relatively new method for measuring volumetric soil moisture content. Its theoretical base was first developed by Fellner-Feldegg (1969), who studied the frequency dependence of the dielectric constant and measured the molecular relaxation times and connected electrical conductivities of liquids. The usefulness of TDR method in measuring soil moisture content was first shown by Topp et al. (1980) and by Smith and Patterson (1980). They found a unique relation between the volumetric moisture content and the apparent dielectric constant of soils.

A great advantage of TDR is, unlike other methods based on the determination of electrical capacitance, that the measured values are not altered by salt and electrolyte content of the soil solution (Dalton and van Genuchten,

1986) . A further advantage is that the soil volume and layer depth studied is a function of the construction of the electrode. In addition to the determination of average moisture content of a soil layer it is also possible to study moisture distribution or movement if one subdivides the soil layer by using divided electrodes (Topp and Davis, 1985). Seasonal, including winter, regimes of soil moisture can be monitored, as shown by Rydén (1986). The TDR method is suitable for making great numbers of field measurements, and consequently well suited for studying spatial distribution of soil moisture content. This paper concerns a study of this kind, comparing statistical and spatial behaviour of soil moisture content data, measured by TDR and gravimetry.

MATERIALS AND METHODS

Theory

Principles of the TDR method can be found elsewhere (e.g. Fellner-Feldegg, 1969; Dalton and van Genuchten, 1986; Smith and Patterson, 1980; Topp et al., 1980, 1982a,b; Topp and Davis, 1985).

The dependence of the dielectric constant of soils on the volumetric water content was determined empirically in the laboratory by Topp et al. (1980). They measured the dielectric constant of a wide range of soils placed in a coaxial transmission line. Later they applied parallel transmission lines (PTL) for the measurements in field situations (Topp et al., 1982b). In this measuring arrangement the high-frequency (20 MHz–1 GHz) pulse travels through the length (L) of the electrode and is reflected at the end of the rods. Thus, the signal travels the double length of the electrodes. The travel velocity (v, cm/s) of the signal can be expressed as:

$$v=2L/t \qquad (1)$$

where L is the length of the electrode (cm), and t is the travel time of the TDR signal (s).

The velocity of a signal (v) can also be expressed by the dielectric constant (K') and the speed of light in vacuum ($c=3\times10^8$ m/s):

$$v=c/(K')^{1/2} \qquad (2)$$

Combining eqs. (1) and (2), the dielectric constant of the material can be defined directly from the travel time. Topp and co-workers (1980) derived a relation between the apparent dielectric constant (K_a) of the soil and its volumetric moisture content (θ_v) as follows:

$$\theta_v=-5.3\times10^{-2}+2.92\times10^{-2}K_a-5.5\times10^{-4}K_a^2+4.3\times10^{-6}K_a^3 \qquad (3)$$

Equation (3) was shown to be valid regardless of the texture, bulk density and organic matter content of soil.

Measurements and evaluations

The measurements in the present study were made using a Tektronix 1502 type cable tester and a PTL probe ($L=10$ cm, $d=0.3$ cm and distance between rods is 2.5 cm) without impedance matching unit between the rods and the coaxial cable.

Measurements were made on a 6 m×10 m size plot within a 0.5 m regular grid (Fig. 1) by pushing the TDR probe into the soil surface (0–10 cm). Immediately after recording the TDR trace, a soil sample for oven-dried gravimetric moisture determination was taken using a corer with 3 cm inner diameter. Travel time was read from the recorded TDR traces as indicated in Fig. 2. Altogether 273 TDR measurements and 273 gravimetric samples were taken on 4 September 1988, 10 days after the harvest of a barley crop. The combine harvester had left visible wheel tracks, as indicated in Fig. 1.

TDR and gravimetric moisture content values were analysed by statistical methods. The normality of the original, detrended and smoothed soil moisture data were analyzed by using the Kolmogorov and Smirnov goodness of fit test. A linear trend was recognized in eastern direction in both moisture data sets, and a periodic trend was established for TDR moisture content data in northern direction.

Linear trends were removed by fitting straight lines by linear regression to the 21 means in eastern direction calculated from 13 moisture content data in northern direction (Fig. 3a). The periodic trend recognized in northern direction on the TDR moisture content data was handled by adjusting to the mean of each 13 lines in northern direction by adding or subtracting their deviation from the common mean (Fig. 3b). The treated data sets were finally smoothed by the T4253H compound smoothing technique, using the SPSSPC+, V3.0 program package.

The results of detrending and smoothing were checked by the periodograms calculated before and after detrending and smoothing. Periodograms (not shown) were calculated using fast-Fourier transformation of the 13 means of 21 moisture content values each, in northern direction. Semivariograms of the detrended residuals of TDR and GM soil moisture contents were calculated to find their spatial behaviour and to check isotropy. Soil bulk density B_d was calculated from the two soil moisture content series according to:

$$\theta\ (\mathrm{g/cm^3}) = B_d(\mathrm{g/cm^3}) \times w\ (\mathrm{g/g}) \qquad (4)$$

where θ and w are the volumetric (TDR) and gravimetric (GM) soil moisture content, respectively.

The standard errors of the sample means were calculated from the standard

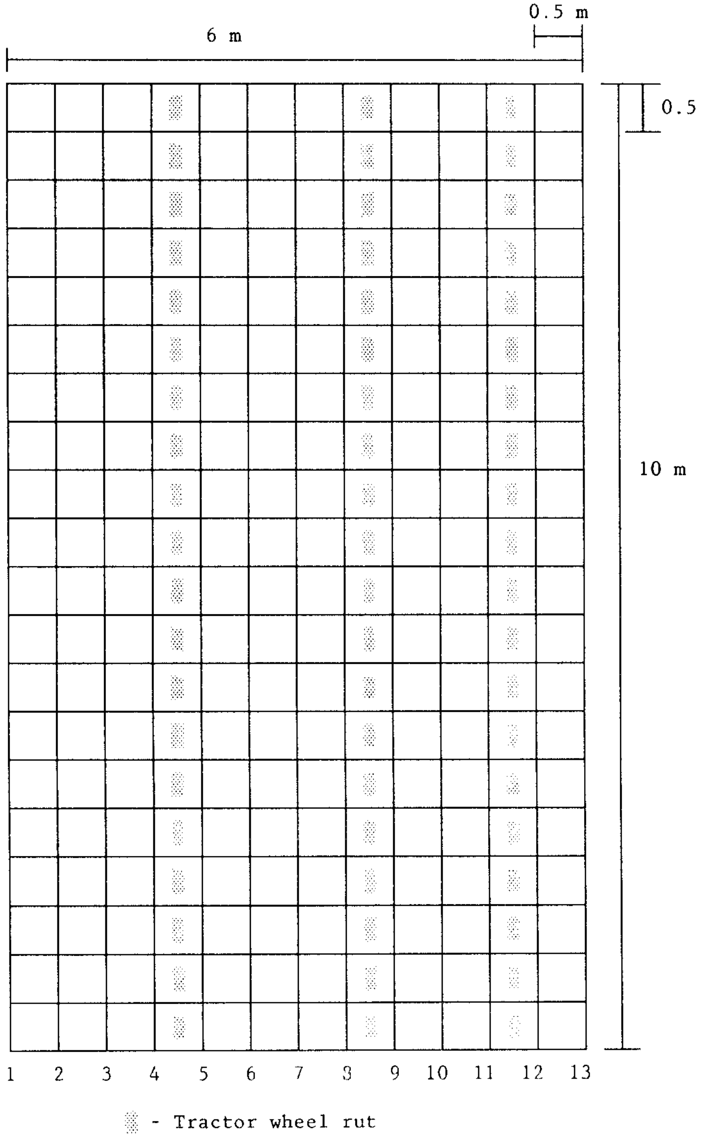

Fig. 1. Layout of the study field.

deviations (s) of the detrended residuals. The standard error of the mean (SE) is assumed to relate to the number of samples (n) through:

$$\mathrm{SE} = s/\sqrt{n} \tag{5}$$

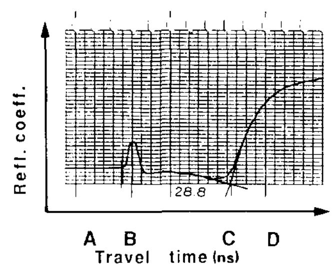

Fig. 2. TDR record and its interpretation. A = Trace of 50 Ω coaxial cable; B = start of parallel transmission line; C = end of parallel transmission line; D = open circuit. B–C represent the travel time of pulses in the soil.

TABLE 1

Main soil characteristics (Fluventic Eutrocrept)

Texture			Bulk density (g/cm^3)	Organic matter (%)	pH$_{H_2O}$
Sand (%)	Silt (%)	Clay (%)			
	0–15 cm		0–5 cm	0–15 cm	
12.2	36.1	51.7	1.22	7.1	7.4
	15–30 cm		10–15 cm	15–30 cm	
11.3	35.2	53.5	1.18	6.8	7.6

Soil properties

The soil of the study area was developed on post-glacial alluvial deposits about 70 cm thick, which covers glacial deposits. This soil type, gyttja, indicates that the soil was formed under the sea level and under the influence of organic deposition during the glacial period. In the FAO soil classification its category is Fluventic Eutrocrept. Some properties of the topsoil are summarized in Table 1. The soil shows a relatively good structure of fine subangular blocky elements. This structure is reflected by low bulk density values, which is typical for soils with "gyttja" properties. A gradual increase of clay content along the down slope (Easterly) direction was observed (Andrén et al., 1990).

RESULTS AND DISCUSSION

Soil moisture content and bulk density

The distributions of measured soil moisture values were normal for GM and significantly different from the normal for TDR values. Neither de-

TABLE 2

Kolmogorov and Smirnov goodness of fit test of normality

Variable	Mean	SD	$K-SZ$	P
Measured data				
TDR	34.78	3.27	1.866	0.002
GM	33.17	1.83	1.180	0.124
Detrended and smoothed data				
TDR	32.91	1.37	1.330	0.058
GM	32.14	1.08	1.303	0.067
Residuals				
TDR	−0.03	1.81	1.063	0.203
GM	−0.03	1.29	0.977	0.296

trended and smoothed moisture values nor their residuals were deviating significantly from the normal distribution shown by the Kolmogorov and Smirnov goodness of fit test (Table 2).

An increase along the down slope (E) for both moisture patterns can be observed in Figs. 3a and 4. This non-random increase of moisture content can be seen on the mean values calculated in that direction (Fig. 3a) and read from the significances of the fitted straight regression lines. Moreover it can be attributed to the slope of the plot and the increase of soil clay content in this direction (Andrén et al., 1990).

At the time of moisture measurements tractor wheel ruts, remaining from the harvest, were clearly visible on the soil surface. The effects of two of the three roughly 30 cm wide ruts parallel with the sample lines in eastern direction, indicated in Fig. 1, can be discovered in Figs. 3b, 4a and 4c. As the figure patterns show, the wheel rut effects can be seen as higher TDR and bulk density values of the mean in northern direction along the strips Nos. 4–5 and 8–9. The third rut effect along the strips Nos. 11–12 is not clearly noticeable in the higher moisture contents.

The areal distributions of the two moisture measurements shown in Figs. 4a and 4b look different, and they were significantly different even after detrending and smoothing according to the paired t-test. However, the detrended residuals of the two moisture measuring methods were not significantly different (Table 3).

One can conclude that the two moisture measuring methods reflect different aspects of the areal distribution of soil moisture contents.

The difference of soil moisture patterns in Figs. 4a and 4b may be due to the fact that TDR and GM measurements represent soil moisture values based on volume and mass ratios, respectively. These two series of soil moisture

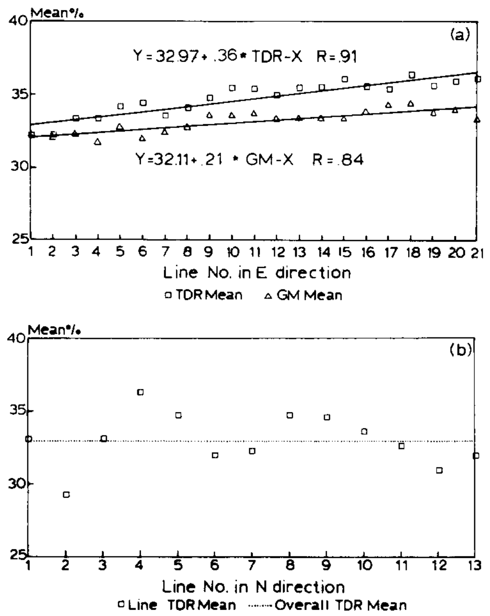

Fig. 3. (a) Linear trend on TDR and GM moisture data in eastern direction. Mean of 13 data in N direction (*y*-axis). (b) Periodic trend on TDR moisture data in northern direction. Mean of 21 data in eastern direction (*y*-axis).

values can be converted into each other if one knows the bulk density of the soil. Since, in our case, measured bulk density values were not available, this conversion could not be done.

However, it is obvious that the bulk density of the soil surface in the wheel ruts was different from that between them. To judge about the variation of the soil bulk density, the TDR and GM measurements were used to calculate bulk density by using eq. (4). The reality of the calculated soil bulk densities can not be checked but they are in good agreement with the experienced moisture content variation in northern direction (Fig. 3b).

The similarity of the areal distribution of the measured TDR moisture content values and the calculated bulk densities in Figs. 4a and 4c might be the consequence that GM moisture content values do not reflect the soil bulk density directly.

Wheel rut effect can also be seen as expressed anisotropy on the semivariograms calculated in northern and eastern directions from the measured TDR data but do not appear on GM semivariograms. The semivariogram shows that variance for lag separations in the range around 2 m was less than for those with separations of 0.5 to 1 m. (Fig. 5a). Perhaps this has resulted from the wheel compaction reducing the variability which tends to occur in the non-compacted soil.

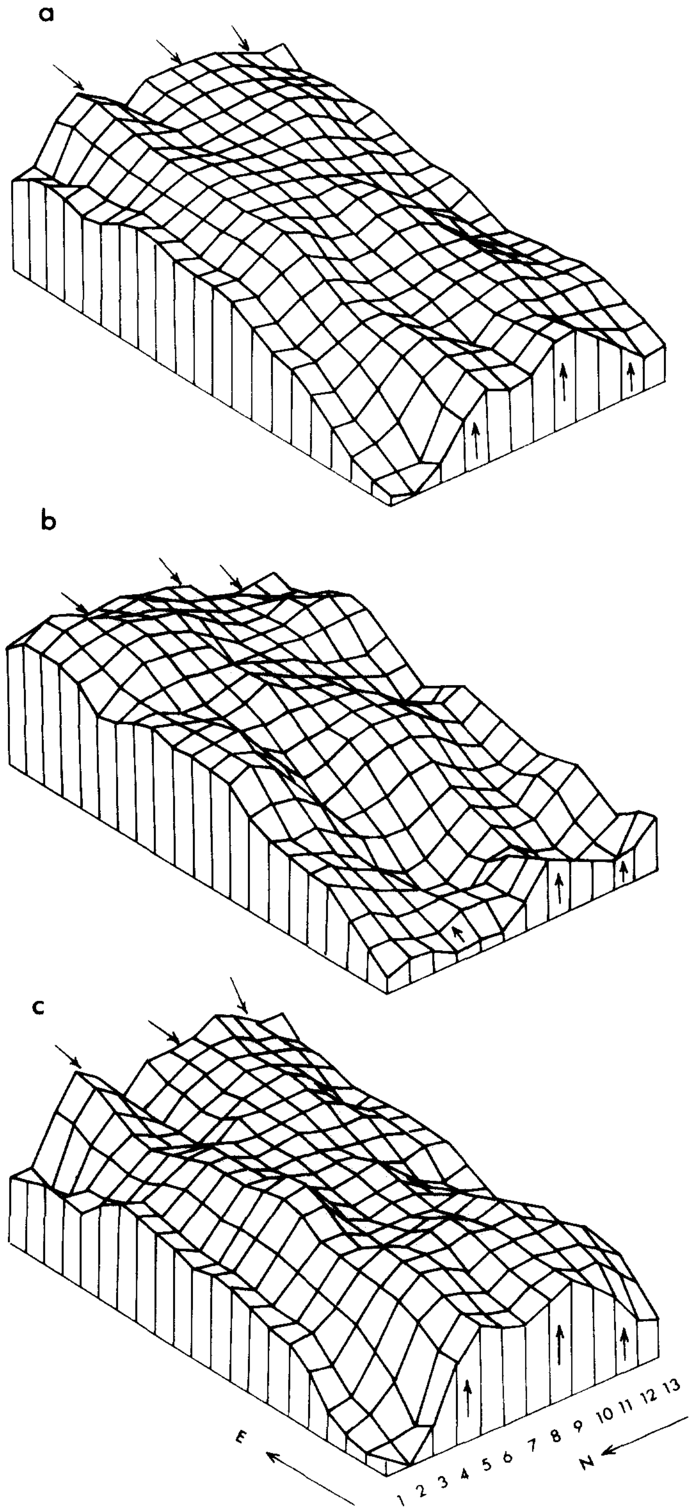

Fig. 4. (a) Areal pattern of TDR soil moisture content values. N = orientation north; E = orientation east, downslope. (b) Areal pattern of gravimetric soil moisture content values. (c) Areal pattern of calculated soil bulk density values.

TABLE 3

Paired samples t-test of TDR and GM data

(Difference) Mean	SD	SE	t-Value	DF	2-Tail probability
Measured data					
1.6004	3.230	0.195	8.19	272	0.000
Detrended data					
0.7804	2.542	0.154	5.07	272	0.000
Detrended and smoothed data					
0.7722	1.488	0.090	8.58	272	0.000
Residual					
0.0081	2.058	0.125	0.07	272	0.948

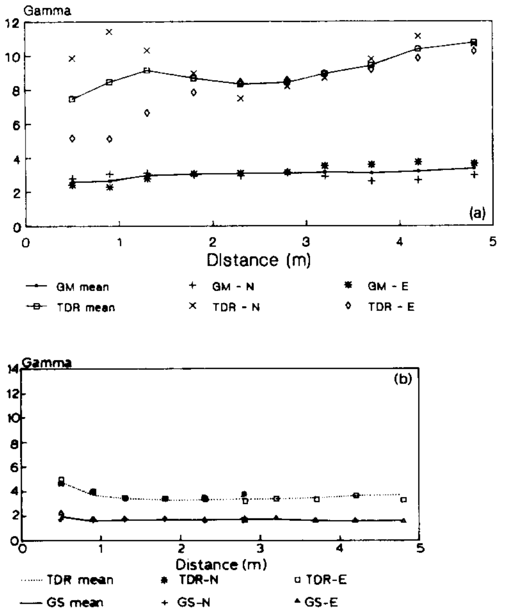

Fig. 5. (a) Semivariograms of original TDR and GM soil moisture contents. (b) Semivariograms of detrended residuals of TDR and GM moisture contents.

Statistical analysis

The isotropic semivariograms of soil moisture values in eastern and northern directions calculated from detrended and smoothed residuals are shown in Fig. 5b. The isotropic semivariances in the two perpendicular directions of

GM measurements are distributed along a line parallel to the x-axis. This means that GM does not have a spatial structure and shows isotropy in the study plot on this scale (0.5 m sampling distance).

Detrended TDR semivariograms show about 2 times higher variance than that of GM. The isotropic semivariogram of TDR residuals also shows a structureless spatial behaviour. Semivariograms calculated in northern and eastern directions behave isotropically similar to those based on GM. These semivariograms suggest that both methods describe soil moisture distribution as a random process. The differences between the semivariograms reflect that TDR measurements have a higher variance.

The coefficient of variation (CV) of soil moisture content changes with the level of soil moisture content. The lower the soil moisture content, the higher the CV (Nielsen et al., 1973). Since only one moisture content status of the soil was measured, CV can characterize the measuring method itself of the original TDR moisture values is about three times higher than CV of the GM moisture content data and remains about double for the detrended residuals (Table 4). Thus the volumetric moisture content can be considered more highly variable.

The linear correlation between the TDR and the gravimetric data is low ($R=0.302$), and becomes lower ($R=0.154$) after detrending, but remains significant. One of the reasons of this decrease might be that one common property from the two data sets – i.e., the moisture values increase in downslope direction – has been removed (Table 5).

TABLE 4

Statistics of TDR, GM data of sample plot

Variable	Mean	SD	SE	CV (%)	Min.	Max.	N
Measured data							
TDR	34.78	3.27	0.20	10.69	18.20	42.60	273
GM	33.18	1.83	0.11	3.36	26.70	37.90	273
Detrended data							
TDR	32.89	2.37	0.14	5.63	23.20	38.61	273
GM	32.11	1.71	0.10	2.94	26.38	36.94	273
Detrended and smoothed data							
TDR	32.91	1.37	0.08	1.89	28.74	36.69	273
GM	32.14	1.08	0.65	1.17	28.70	35.11	273
Residual							
TDR	−0.03	1.81	0.11	3.29	−7.50	5.61	273
GM	−0.03	1.29	0.08	1.68	−5.33	4.13	273

TABLE 5

Correlations of TDR and GM moisture data

TDR and GM	R	Sign.
Measured	0.302	0.000
Detrended and smoothed	0.283	0.000
Residuals	0.154	0.011

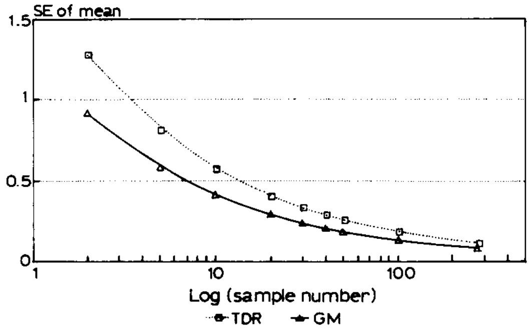

Fig. 6. Standard error of the mean as a function of sample number for detrended residuals of soil moisture contents.

Since our measurements refer to a set of only one soil moisture content status, we studied the behaviour of the standard error of the estimated mean assuming that the sample population is normal, which is valid for the detrended residuals (Fig. 6).

This figure suggests that in the soil moisture content range of the study plot moisture content can be estimated with about ±0.5% of error by taking 13 TDR measurements. The corresponding number for GM is 7 samples. However, accepting 1% of random error, only 2 GM or 3 TDR measurements are necessary.

Our measurements draw attention to the sensitivity of TDR measurements to indicate properties not reflected by the GM values. This resulted in at least two times higher CV values of the TDR records compared with the GM measurements (Table 4).

Studying the different installation techniques of the TDR electrodes into the soil, it was concluded that a slight local variation of the soil bulk density is reflected in the higher variation of soil moisture content (Topp et al., 1982b). In another paper the soil bulk density was established as a factor that does not affect the relationship between moisture content and dielectric constant of the soil (Topp et al., 1980).

Thus, we have found a field example in which the soil moisture pattern of the TDR measurements can be attributed to the observable, induced soil bulk density pattern. It can also be concluded that the TDR is a technique with which the spatial variation of soil moisture content can be studied with sufficient efficiency on an appropriate spatial scale for analytical methods.

SUMMARY

The TDR method was used for measuring surface (0–10 cm) soil moisture content of a field plot (Table 1). Within a regular grid scheme (Fig. 1), 273 points were measured by TDR and sampled for GM soil moisture content determination after the harvest of a barley crop. Both soil moisture content determination methods produced moisture content data, which were normally distributed after detrending (Table 2).

The areal distributions of soil moisture content values showed different patterns (Figs. 4a and 4b). Semivariograms of detrended residuals of soil moisture content data (Fig. 5b) reflected a structureless spatial behaviour. The indicated random areal distribution of soil moisture content allows a random sampling of the field. This is why the error term of the sample mean, as a function of sample size, was also calculated (Fig. 6).

TDR moisture content data reflected a soil moisture pattern of the study plot caused by tractor wheels (Fig. 4b). However, this did not cause significant statistical difference between TDR and gravimetric soil moisture content values when the trend from each soil moisture content data set has been removed (Tables 2 and 3).

The presented field application of the TDR method illustrates its applicability in studying areal distribution of soil moisture content. The present study draws attention to the influence of soil bulk density on the interpretation of field measured TDR moisture content pattern.

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