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COMPARISON OF SOIL THERMAL PROPERTIES IN CULTIVATED FIELDS DETERMINED USING SOIL WATER CONTENT MEASURED BY TWO METHODS*

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Abstract. Results of the measurements of water content in the topsoil layer (1-6 cm) in fields with various crops obtained by gravimetric and reflectometric (TDR) methods have been used for the calculations of soil volumetric heat capacity, thermal conductivity, and diffusivity. Calculation values of individual soil thermal properties obtained in the two ways were then analysed by means of statistical and geostatistical methods and compared (correlation coefficients, regression equations, difference distributions, mean square errors, and maximum relative errors were determined). Compatibility of values of thermal properties as determined on the basis of soil moisture measured by means of gravimetric and TDR methods, was generally speaking, satisfactory, even though not uniform in various soil moisture ranges; it is better with higher moisture levels, and worse when moisture levels were low. More accuracy in spatial distribution of thermal properties obtained on the basis of soil moisture as measured by gravimetric than by reflectometric method points to the lower sensitivity of the TDR method for the soil moisture measurements.

Keywords: soil thermal properties, soil water content, TDR methods

INTRODUCTION

The physical relations between soil thermal properties and soil water content are well-known. At a given soil bulk density the volumetric heat capacity is linearly dependent upon soil water content whereas non-linear dependencies occur in the case of soil thermal conductivity and diffusivity. As a consequence, the same increment of water content (e.g., by 0.01 $m^3 m^{-3}$) causes different changes of thermal conductivity and diffusivity values at different levels of soil water content (relatively highest in the range of small soil water content).

As a rule, calculation methods are used in order to determine soil thermal properties in field conditions. They are based on the contents of mineral particles, organic matter, water and air in the unit of soil volume, as well as on the heat capacity or thermal conductivity of each of the soil components, respectively, when volumetric heat capacity or thermal conductivity of the soil is determined. When studies concern variability of soil thermal properties of the same soil in time or space, differentiation of these properties is determined by the changes in volumetric water, air and solid phase content [16,18]. Measurements of soil water content and soil bulk density are then of fundamental importance, and their accuracy influences values of individual soil thermal properties.

In order to arrive at a representative statistical description of the soil physical properties in the study object, it is necessary to determine the functions of probability density, mean value and variance. In the soil area, however, the variable values are usually spatially interrelated, and it is necessary to use semivariogram parameters to statistical descriptions of a

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given variable. When such an complete description is known, it is feasible to state the optimal number of samples, spatial lag and net configuration of sampling additionally [9,20].

The oldest method of determining soil moisture content, i.e., the gravimetric method, is considered to be the standard one. The newest, that is becoming more and more popular is the reflectometric (TDR) method. To name a few positive features of this method, we can say that it is non-destructive and far easier (less laborious) than the gravimetric method in the case of multi-point moisture measurements in the study object. Results of soil moisture measurements by means of the gravimetric and TDR methods, as a rule, showed satisfactory compatibility in mean values; they were less satisfactory in regard to dispersion of soil moisture values [1,3,7,8,15]. At the same time the spatial distribution of soil water content as obtained on the basis of the two methods differed, and the range of difference was influenced by the degree of water saturation and soil compaction [11,15].

The aim of the present paper was to investigate conformity of statistical characteristics and spatial distributions of the soil thermal properties in cultivated fields as determined from mathematical models using soil water content obtained by gravimetric or reflectometric methods.

STUDY OBJECT AND METHODS

The present work used data obtained from the measurements of topsoil (1-6 cm) moisture and bulk density carried out during two vegetation seasons in the fields with various crops in Felin near Lublin. Loess-like, silty soil (Orthic Luvisol developed from silt formations) was a typical mineral soil. The mean density of the solid phase in the arable layer was 2.65 Mg m^{-3}, and the contents of organic matter, quartz, and other minerals was, respectively, 0.015, 0.67, 0.315 $m^3 m^{-3}$.

The study object consisted of adjacent fields of cabbage, sugar beet, winter wheat, maize, and potato (season 1992), and maize and spring wheat (season 1993). In the 1992 season measuring points were located in the nods of a square grid with 10 m long side, and formed a strip running through the field covering the area of 40x430 m. In 1993 season the grid of nods with 10 m spacing covered the area of 90x200 m; in the maize field additional measurements in the square grid with the 2 m sides and covering the area of 20x20 m were carried out.

In order to determine soil moisture using the reflectometric method (θ_{TDR}) a TDR meter manufactured by Easy Test Ltd, Lublin, Poland [6] was used. At the same time, soil samples were collected from the same points into cylinders with 100 cm^3 volume and 5 cm high in order to determine soil bulk density (ρ) and soil moisture by means of the gravimetric method (θ_{GRAV}). Results of the measurements, including the spatial distributions, were compared and discussed in another paper [15].

Soil thermal conductivity (λ) was calculated using a statistical-physical model [13, 14], volumetric heat capacity (Cv) using de Vries formula [17]:

$$C_v = (2.0f_m + 2.51f_o + 4.18\theta_v)*10^6 \text{ (J m}^{-3}\text{ K}^{-1})$$

where : f_m, f_o and θ_v ($m^3 m^{-3}$) are the minerals, organic matter and water contents, respectively. Thermal diffusivity (k) was calculated from the ratio of these thermal properties.

The model of soil thermal conductivity has been designed on the basis of the thermal resistance being one of the fundamental properties characterising the ability of a given body to conduct heat, serial and parallel connections of the thermal resistors, and statistical polynomial distribution allowing for the calculation of the probability (P) of the occurrence of all the possible configurations of particles (x_i) that take part in heat conduction [13]. A unit volume of soil consisting of solid particles, water and air is presented as a system composed of elementary geometrical figures. In this case they are spheres of specific properties ($\lambda_1 ... \lambda_k$ - thermal conductivity of different soil components, $r_1 ... r_k$ - sphere radius, T - temperature), forming overlapping layers. It has been assumed that contacts between spheres within a layer and between layers will be represented by a parallel connection of thermal resistors (u) such as the spheres in a layer and by serial connections between the layers (n). A comparison of the resultant resistance of the parallel-series system of resistors with the mean thermal resistance of the unit soil volume followed by some transformations, gave a general formula for the average thermal conductivity (λ, W m^{-1} K^{-1}):

$$\lambda = \frac{4\pi}{u \sum_{j=1}^{n} \frac{P\left(x_{1j},\ldots,x_{kj}\right)}{x_{1j}\lambda_1(T)r_1+\ldots+x_{kj}\lambda_k(T)r_k}}$$

$$P\left(x_{1j},\ldots x_{kj}\right) = \frac{u!}{x_{1j}!\ldots x_{kj}!} f_1^{x_{1j}} \ldots f_k^{x_{kj}}$$

where: $f_1,\ldots f_k$ denote the content of particular minerals, organic matter, water and air in the soil unit volume, and L is the number of all possible combinations of particles locations. The model modifies the number of parallel connections together with the change of soil water saturation, as well as a sphere radius of particles (r_k) with the change of organic content (f_o) according to the formula: $r_k = 0.036 f_o + 0.044$. The mean square error of thermal conductivity estimated by the model is about 0.06 W m^{-1} K^{-1} [13].

The calculations of soil thermal properties for every measuring point were performed twice: 1) on the basis of the soil water contents determined by the gravimetric method, and 2) the soil water contents from reflectometric method. In both cases the same mean values regarding mineralogical composition, organic matter content, particle density and temperature (25 °C), as well as the same measured values of soil bulk density were used. Thus, fluctuations other than soil water content and bulk density parameters within investigated fields were not taken into consideration.

Statistical characteristics of the individual soil thermal properties have been determined for a given cultivated field, and for all the measuring points jointly (556 pairs of data). A comparison between the values of thermal properties as calculated on the basis of the soil moisture measurements by the two a.m. methods (correlation coefficients, regression equations, differences in values, and others) was carried out. On the basis of data from individual fields (with the number of measuring points higher than 40) and from a chosen group of fields, analyses of spatial variability of soil thermal properties using geostatistical methods haven been conducted [5,9,10,12,19]. Parameters of semivariograms were determined, and mathematical functions were fitted for the empirically obtained semivariograms. These fun-ctions were then used for the estimation of the spatial distributions of soil thermal properties in the cultivated fields using the kriging method [4].

RESULTS

Statistical analyses of the values of individual soil thermal properties as calculated from the moisture data obtained by the gravimetric method (θ_{GRAV}) and TDR method (θ_{TDR}) showed a better conformity in the values of soil thermal properties than soil moisture (Tables 1 and 2). The above statement is valid for the values obtained for the individual crop fields, and all the fields (data) considered jointly, for percentage differences between mean values and standard deviation values, as well as for the correlation coefficients.

The highest difference of 14% between the mean values of soil water content obtained from TDR and gravimetric methods was noted in the sugar beet field [15], whereas the differences between mean values of thermal conductivity, heat capacity and thermal diffusivity of soil in the same field (it happened to be the biggest of the fields studied) were lower, i.e., 12 %, 6 % and 7 %, respectively. Similarly as in the case of soil water content, in the majority of fields mean and extreme values of individual soil thermal properties as calculated from θ_{TDR} were higher.

In majority of the studied crop fields higher values of standard deviation (SD) of soil thermal conductivity and diffusivity were

T a b l e 1. Statistical summary of topsoil thermal properties obtained on the basis of gravimetric (Grav) and TDR water content data

Statistics	Cabbage 17.06.1992 n=30		Sugar beet 17.06.1992 n=60		Maize 26.06.1992 n=45		Winter wheat 9.07.1992 n=60	
	Grav	TDR	Grav	TDR	Grav	TDR	Grav	TDR
Conductivity (W $m^{-1}K^{-1}$)								
mean	1.011	1.074	1.243	1.388	1.528	1.540	1.405	1.392
maximum	1.633	1.658	1.882	1.890	1.989	1.988	1.903	1.872
minimum	0.448	0.469	0.461	0.678	0.856	0.902	0.981	1.055
St. deviation	0.295	0.267	0.368	0.276	0.278	0.259	0.189	0.171
Coef. variation (%)	29.2	24.8	29.6	19.9	18.2	16.8	13.5	12.3
Skewness	-0.229	-0.122	-0.466	-0.660	-0.522	-0.486	0.086	0.238
Kurtosis	2.580	3.129	2.357	2.980	2.613	2.850	2.482	2.470
Capacity (MJ $m^{-3}K^{-1}$)								
mean	1.661	1.705	1.763	1.861	2.029	2.053	1.841	1.822
maximum	1.869	1.952	2.093	2.144	2.429	2.420	2.238	2.183
minimum	1.433	1.391	1.388	1.547	1.640	1.691	1.621	1.672
St. deviation	0.110	0.117	0.172	0.133	0.186	0.172	0.111	0.090
Coef. variation (%)	6.6	6.9	9.7	7.1	9.2	8.4	6.0	5.0
Skewness	-0.211	-0.310	-0.341	-0.203	-0.036	-0.113	0.742	0.902
Kurtosis	2.581	3.608	2.515	2.941	2.383	2.508	4.309	5.613
Diffusivity ($10^{-7}m^2s^{-1}$)								
mean	6.003	6.230	6.910	7.392	7.471	7.459	7.603	7.617
maximum	8.737	8.491	9.021	8.938	8.635	8.580	8.656	8.757
minimum	3.073	3.372	3.310	4.387	5.182	5.234	6.051	6.260
St. deviation	1.426	1.199	1.529	1.048	0.812	0.765	0.624	0.608
Coef. variation (%)	23.8	19.2	22.1	14.2	10.9	10.3	8.2	8.0
Skewness	-0.489	-0.422	-0.817	-1.037	-0.929	-0.903	-0.314	-0.054
Kurtosis	2.565	3.150	2.700	3.684	3.416	3.537	2.217	2.049

n- number of points.

Table 1. Contninuation

Statistics	Spring wheat 6.07.1993 n=80		Maize (spacies 10 m) 6.07.1993 n=70		Maize (spacies 2 m) 15.07.1993 n=121		All the data 1992 and 1993 n=556	
	Grav	TDR	Grav	TDR	Grav	TDR	Grav	TDR
Conductivity (W $m^{-1}K^{-1}$)								
mean	0.490	0.521	0.820	0.864	0.719	0.699	0.925	0.950
maximum	1.168	1.370	1.764	1.766	1.299	1.476	1.989	1.988
minimum	0.268	0.168	0.341	0.321	0.397	0.401	0.268	0.168
St. deviation	0.125	0.168	0.381	0.390	0.220	0.207	0.437	0.443
Coef. variation (%)	25.5	32.3	46.4	45.1	30.7	29.6	47.2	46.6
Skewness	2.027	1.869	0.829	0.481	1.143	1.621	0.487	0.374
Kurtosis	12.393	10.983	2.559	2.058	3.348	5.458	1.941	1.803
Capacity (MJ $m^{-3}K^{-1}$)								
mean	1.317	1.359	1.561	1.570	1.500	1.492	1.608	1.626
maximum	1.652	1.713	1.950	1.958	1.740	1.871	2.429	2.420
minimum	1.163	1.082	1.255	1.211	1.274	1.268	1.163	1.082
St. deviation	0.092	0.125	0.157	0.167	0.112	0.116	0.246	0.251
Coef. variation (%)	7.0	9.2	10.1	10.6	7.5	7.7	15.3	15.4
Skewness	0.882	0.359	0.369	0.064	0.218	0.836	0.532	0.418
Kurtosis	4.272	2.755	2.661	2.467	2.307	3.763	2.750	2.559
Diffusivity ($10^{-7}m^2s^{-1}$)								
mean	3.683	3.766	5.075	5.312	4.719	4.618	5.491	5.577
maximum	7.072	8.000	9.043	9.019	7.629	7.889	9.046	9.019
minimum	2.303	1.553	2.645	2.568	2.969	2.986	2.303	1.553
St. deviation	0.663	0.866	1.831	1.884	1.079	0.964	1.835	1.852
Coef. variation (%)	18.0	23.0	36.1	35.5	22.9	20.9	33.4	33.2
Skewness	1.532	1.362	0.666	0.334	1.155	1.449	0.242	0.141
Kurtosis	10.323	10.457	2.133	1.748	3.434	4.808	1.613	1.603

Table 2. Comparison of topsoil thermal properties obtained on the basis of gravimetric (Grav) and TDR water content data

Thermal property	Cultivated field	Correlation coefficient	Regression equation	Mean square error	Maximum relative error (%)
Conductivity λ ($Wm^{-1}K^{-1}$)	Cabbage 17.06.1992	0.874	$\lambda_{TDR} = 0.790\,\lambda_{Grav} + 0.275$	0.154	71.7
	Sugar beet 17.06.1992	0.916	$\lambda_{TDR} = 0.687\,\lambda_{Grav} + 0.535$	0.215	88.8
	Maize 26.06.1992	0.946	$\lambda_{TDR} = 0.881\,\lambda_{Grav} + 0.194$	0.091	24.9
	Winter wheat 9.07.1992	0.875	$\lambda_{TDR} = 0.793\,\lambda_{Grav} + 0.278$	0.092	19.3
	Spring wheat 6.07.1993	0.839	$\lambda_{TDR} = 1.127\,\lambda_{Grav} - 0.032$	0.097	74.6
	Maize (spacing of 10 m) 6.07.1993	0.956	$\lambda_{TDR} = 0.979\,\lambda_{Grav} + 0.062$	0.122	57.5
	Maize (spacing of 2 m) 15.07.1993	0.698	$\lambda_{TDR} = 0.655\,\lambda_{Grav} + 0.229$	0.167	96.2
	All the data 1992 and 1993	0.937	$\lambda_{TDR} = 0.950\,\lambda_{Grav} + 0.071$	0.157	105.9
Capacity Cv ($MJm^{-3}K^{-1}$)	Cabbage 17.06.1992	0.794	$Cv_{TDR} = 0.849\,Cv_{Grav} + 0.294$	0.084	14.5
	Sugar beet 17.06.1992	0.821	$Cv_{TDR} = 0.635\,Cv_{Grav} + 0.742$	0.139	19.5
	Maize 26.06.1992	0.913	$Cv_{TDR} = 0.846\,Cv_{Grav} + 0.335$	0.079	9.0
	Winter wheat 9.07.1992	0.869	$Cv_{TDR} = 0.707\,Cv_{Grav} + 0.521$	0.058	7.1
	Spring wheat 6.07.1993	0.604	$Cv_{TDR} = 0.816\,Cv_{Grav} + 0.284$	0.109	21.3
	Maize (spacing of 10 m) 6.07.1993	0.932	$Cv_{TDR} = 0.990\,Cv_{Grav} + 0.024$	0.061	16.2
	Maize (spacing of 2 m) 15.07.1993	0.648	$Cv_{TDR} = 0.667\,Cv_{Grav} + 0.492$	0.096	22.3
	All the data 1992 and 1993	0.922	$Cv_{TDR} = 0.939\,Cv_{Grav} + 0.116$	0.100	26.3
Diffusivity k ($10^{-7}m^2s^{-1}$)	Cabbage 17.06.1992	0.877	$k_{TDR} = 0.737\,k_{Grav} + 1.807$	0.714	50.0
	Sugar beet 17.06.1992	0.922	$k_{TDR} = 0.632\,k_{Grav} + 3.026$	0.840	58.0
	Maize 26.06.1992	0.935	$k_{TDR} = 0.881\,k_{Grav} + 0.876$	0.285	15.0
	Winter wheat 9.07.1992	0.846	$k_{TDR} = 0.824\,k_{Grav} + 1.351$	0.340	15.5
	Spring wheat 6.07.1993	0.844	$k_{TDR} = 1.102\,k_{Grav} - 0.293$	0.474	76.1
	Maize (spacing of 10 m) 6.07.1993	0.954	$k_{TDR} = 0.982\,k_{Grav} + 0.329$	0.610	47.4
	Maize (spacing of 2 m) 15.07.1993	0.724	$k_{TDR} = 0.646\,k_{Grav} + 1.569$	0.770	60.3
	All the data 1992 and 1993	0.933	$k_{TDR} = 0.942\,k_{Grav} + 0.406$	0.678	64.4

stated when calculations were carried out using θ_{GRAV}. In the case of volumetric heat capacity this dominance was not observed. It should be noted that the highest, over 30%, differences in standard deviation values of soil thermal properties calculated on the basis of θ_{GRAV} and θ_{TDR} data were noted in the field with the lowest soil moisture content and bulk density (the field with spring wheat); and higher SD values of thermal properties were obtained from θ_{TDR} data. However, in another field (sugar beet) only slightly lower differences of SD values but with higher SD levels calculated on the basis of θ_{GRAV} data were found.

The analysis of differences in the values of standard deviation for the individual thermal properties calculated from θ_{GRAV} and θ_{TDR} data in relation to mean soil water content and bulk density in the seven fields considered (with the number of measuring points higher than 30) showed that these differences were increasing with the increase of soil moisture and bulk density levels. Their values changed sign from negative to positive in the case of differences $SD\lambda_{GRAV}$ - $SD\lambda_{TDR}$, $SDCv_{GRAV}$ - $SDCv_{TDR}$, and SDk_{GRAV} - SDk_{TDR}, when soil moisture and bulk density levels were, respectively, 0.12 m^3 m^{-3} and 1.32 Mg m^{-3}, 0.15 m^3 m^{-3} and 1.34 Mg m^{-3}, 0.10 m^3 m^{-3} and 1.31 Mg m^{-3}. It suggests that when soil bulk density and moisture levels are below these values, the dispersion of thermal properties calculated on the basis of θ_{TDR} is higher than when the values come from θ_{GRAV} and above these values the dispersion of thermal properties calculated on the basis of θ_{TDR} data is smaller. The tendency observed in the changes of differences in standard deviations of soil thermal properties in relation to the value of soil water content and bulk density agrees with the one found for the differences in standard deviations of soil moisture as measured by the gravimetric and TDR methods [15], but the threshold values appeared to be a little lower than in the case of soil water content (0.17 m^3 m^{-3} and 1.35 Mg m^{-3}).

Comparison of soil water content values obtained form the gravimetric and TDR methods and the values of soil thermal conductivity, heat capacity and thermal diffusivity obtained on the basis of these measurements have been presented in Fig. 1. As can be seen, configuration and scatter of points around the 1:1 axis in the case of soil heat capacity and water content was similar, and differed significantly in the case of soil thermal conductivity and diffusivity. Similarity in the graphs depicting soil heat capacity and water content results from the linear relation between this thermal property and soil moisture. The dispersion of soil thermal conductivity and diffusivity values was considerably bigger than in the case of soil water content, especially in the range of intermediate values. It can be explained by the course of relation between these thermal properties and soil water content where in the moisture range from 0.05 m^3m^{-3} to about 0.2 m^3m^{-3} a slight increase in the moisture at a given soil bulk density causes a big change of the soil thermal conductivity and diffusivity values [16]. Taking into consideration the above it may be concluded that the accuracy of measurement of soil moisture exerts a significant influence on the values of soil thermal properties being determined. The mean square error and the maximum relative error calculated for all the data jointly was 0.157 W m^{-1} K^{-1} and 105.9% for thermal conductivity, 0.1 10^6 J m^{-3} K^{-1} and 26.3% for heat capacity, 0.678 10^{-7} m^{-2} s^{-1} and 64.4% for thermal diffusivity, and 0.024 m^3 m^{-3} and 102.2% for soil water content. In individual fields the values of these errors ranged from 0.091 - 0.215 W m^{-1} K^{-1}, and 19.3 - 96.2% in the case of conductivity, 0.058 - 0.139 10^6 J m^{-3} K^{-1} and 7.1 - 22.3% for capacity, 0.285 - 0.84 10^{-7} m^2 s^{-1} and 15.0 - 76.1% for thermal diffusivity, whereas in the case of soil water content it ranged from 0.014 - 0.033 m^3 m^{-3} and 18.1 - 102.2%.

In the linear regression equations for the individual thermal properties determined on the basis of data pairs for all the measuring points jointly and for the individual fields, the direction coefficients were higher than in the analogous equations for the soil water content determined by the gravimetric and TDR

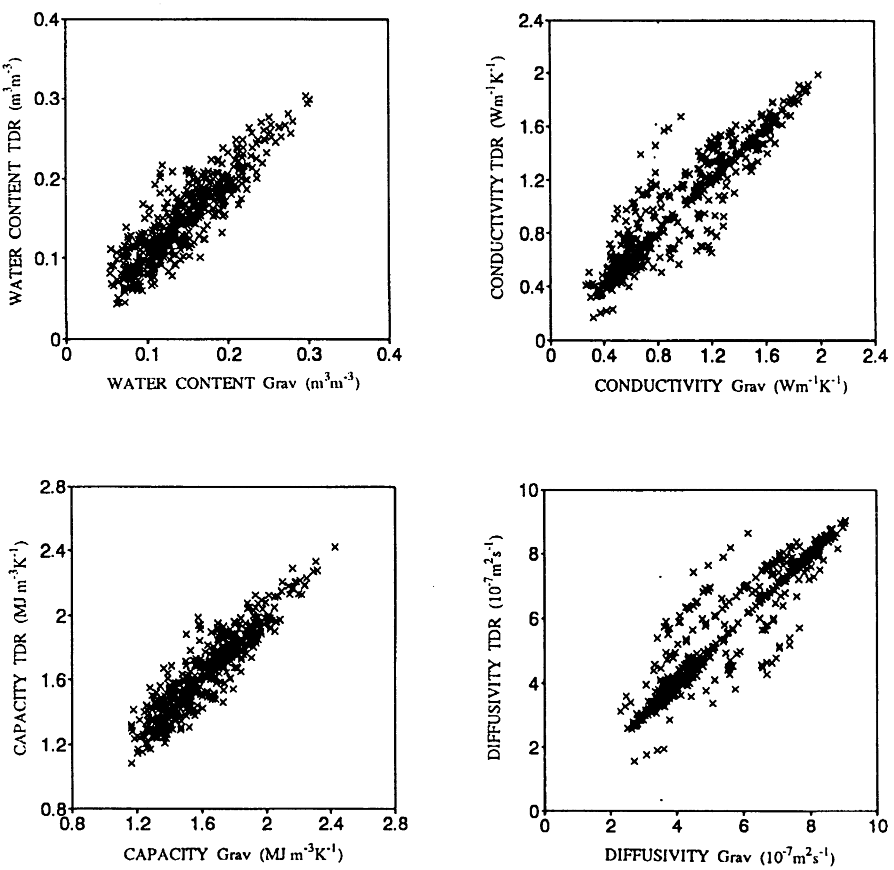

Fig. 1. Soil water content from TDR versus gravimetric measurements and comparison of soil thermal conductivity, volumetric heat capacity and thermal diffusivity obtained on the basis of these two water content data.

methods. These coefficients in the case of soil moisture ranged from 0.469 to 0.912, and for thermal conductivity, heat capacity and thermal diffusivity they ranged, respectively, from 0.655 to 1.127, 0.635 - 0.990, and 0.632 - 1.102. The correlation coefficients for the measuring points treated jointly, i.e., 0.937 for λ, 0.922 for Cv, and 0.933 for k, appeared to be higher than for the soil water content (0.889). An identical situation was observed in the case of individual crop fields. Considering correlation coefficients between thermal properties calculated on the basis of θ_{GRAV} and θ_{TDR} data in the seven fields, it has been found, moreover, that their values depended on the mean soil moisture in a given study object, i.e., the higher soil moisture level, the higher these values were. This relation appeared very clearly in the case of heat capacity but it was also observed for thermal conductivity and diffusivity. It follows from the above that the conformity between these values of soil thermal properties determined on the basis of the θ_{TDR} and θ_{GRAV} data shows a tendency towards improvement with the increase of soil moisture levels.

The analysis of conformity between the empirical distribution of values of individual soil thermal properties and the statistical distribution (normal, lognormal, gamma, etc.) for the study fields treated separately and jointly showed that in the majority of cases these distributions agreed with the lognormal distribution. The above statement is equally true for the thermal properties as calculated on the basis of θ_{TDR} and θ_{GRAV} data.

Differences between soil thermal conductivity, heat capacity and thermal diffusivity values obtained by means of θ_{TDR} and θ_{GRAV} data for the individual measuring points have also been statistically analysed. Taking into account the whole set of 556 points, the mean difference between values for thermal conductivity was -0.025 W m^{-1} K^{-1}, heat capacity -0.018 10^6 J m^{-3} K^{-1}, thermal diffusivity -0.087 10^{-7} m^2 s^{-1}, and the standard deviation for these values was, respectively, 0.156 W m^{-1} K^{-1}, 0.098 10^6 J m^{-3} K^{-1}, 0.673 10^{-7} m^2 s^{-1}. The mean differences of these thermal properties in absolute values were 0.099 W m^{-1} K^{-1}, 0.076 10^6 J m^{-3} K^{-1}, and 0.384 10^{-7} m^2 s^{-1}, respectively. The histograms of the differences in the soil thermal property values for all the data and histogram of the differences in the soil water content have been presented in Fig. 2.

The geostatistical analysis of spatial variability of soil thermal properties has been conducted for seven objects containing enough measuring points for this purpose [2,9,20] (Table 3). In most of these objects, the models of semivariograms and their parameters obtained for the individual soil thermal properties calculated on the basis of θ_{TDR} and θ_{GRAV} data were similar (with the exception of the maize field in which samples were taken every 2 m). This situation was also found in the case of geostatistical characteristics of soil water content obtained from the gravimetric and reflectometric methods [15]. The semivariance values of soil thermal properties calculated with θ_{TDR} where higher than the ones calculated

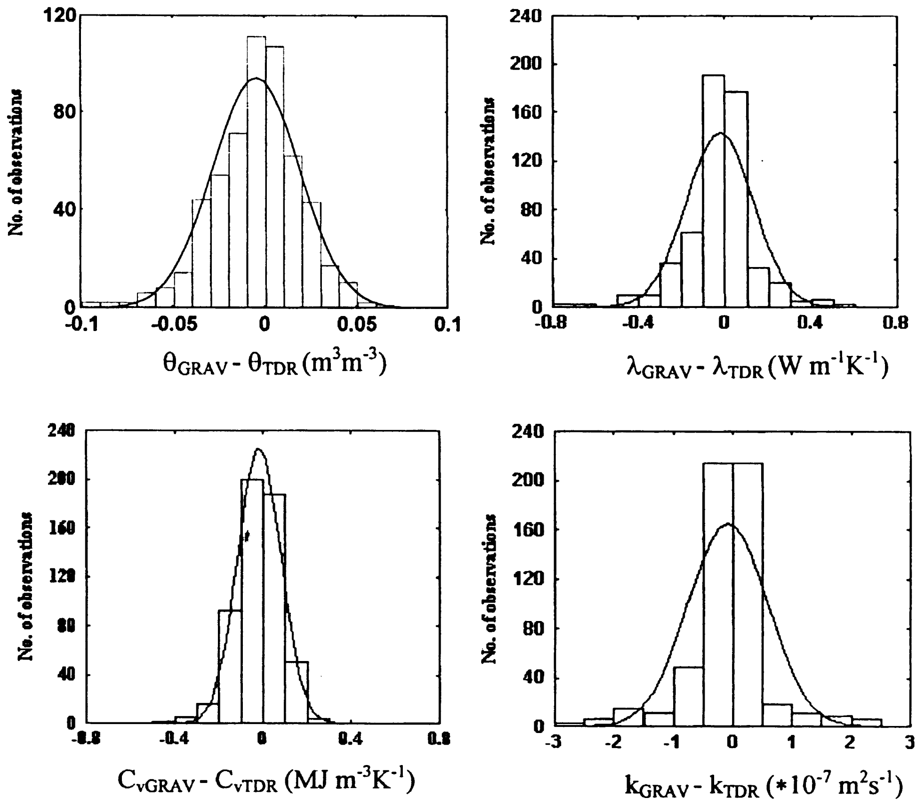

Fig. 2. Normal distributions and histograms of differences between values of topsoil water content (θ), thermal conductivity (λ), volumetric heat capacity (C_v) and thermal diffusivity (k) determined on the basis of gravimetric (Grav) and reflectometric (TDR) water content data.

T a b l e 3. Model and parameters of semivariogram of topsoil thermal properties in chosen culitvated fields obtained on the basis of gravimetric (Grav) and TDR water content data

Cultivated field	Method	Conductivity				Capacity				Diffusivity			
		Nugget $(Wm^{-1}K^{-1})^2$	Sill $(Wm^{-1}K^{-1})^2$	Range (m)	Model	Nugget $(MJm^{-3}K^{-1})^2$ x10^6	Sill $(MJm^{-3}K^{-1})^2$ x10^6	Range (m)	Model	Nugget $(m^2s^{-1})^2$ x10^{-14}	Sill $(m^2s^{-1})^2$ x10^{-14}	Range (m)	Model
Sugar beet 17.06.1992	Grav	0	0.145	25	Exp	0	0.0315	25	Exp	0	2.6	30	Exp
	TDR	0	0.08	25	Exp	0	0.019	30	Exp	0	1.2	25	Exp
Maize 26.06.1992	Grav	0	0.092	40	Exp	0	0.04	45	Exp	0	0.72	30	Exp
	TDR	0	0.08	50	Exp	0	0.035	45	Exp	0	0.6	30	Exp
Winter wheat 9.07.1992	Grav	0	0.037	20	Exp	0.008	0.0095	100	Lin	0	0.445	20	Exp
	TDR	0	0.031	22	Exp	0.005	0.0065	100	Lin	0	0.42	20	Exp
Spring wheat 6.07.1993	Grav	0.016	-	-	Lin	0.0085	-	-	Lin	0.44	-	-	Lin
	TDR	0.028	-	-	Lin	0.015	-	-	Lin	0.75	-	-	Lin
Maize (spacing of 10 m) 6.07.1993	Grav	0.14	-	-	Lin	0.024	-	-	Lin	3.2	-	-	Lin
	TDR	0.14	-	-	Lin	0.028	-	-	Lin	3.4	-	-	Lin
Maize and spring wheat (together) 6.07.1993	Grav	0.04	0.12	180	Sph	0	0.053	160	Sph	0.5	2.9	180	Sph
	TDR	0.05	0.12	180	Sph	0.012	0.035	160	Sph	1.3	2.4	160	Sph
Maize (spacing of 2 m) 15.07.1993	Grav	0.049	-	-	Lin	0.0125	-	-	Lin	1.16	-	-	Lin
	TDR	0.03	0.02	8	Sph	0.08	0.07	8	Sph	0.65	0.43	8	Sph

Explanation: Exp - exponential, Lin - linear, Sph - spherical.

with the use of θ_{GRAV} when soil moisture in the study object was below the threshold values determined at the analysis of differences in the standard deviations. Whereas, when the soil moisture was above these threshold values then higher semivariance values of soil thermal properties as calculated with θ_{GRAV} were observed.

The maps of spatial distribution of individual soil thermal properties calculated on the basis of θ_{TDR} and θ_{GRAV} data showed high similarity. It can be seen in the examples enclosed in Figs 3, 4 and 5 a,b. However, a lower concentration of the isolines in the maps of soil thermal properties calculated on the basis of θ_{TDR} than θ_{GRAV} data, points to the

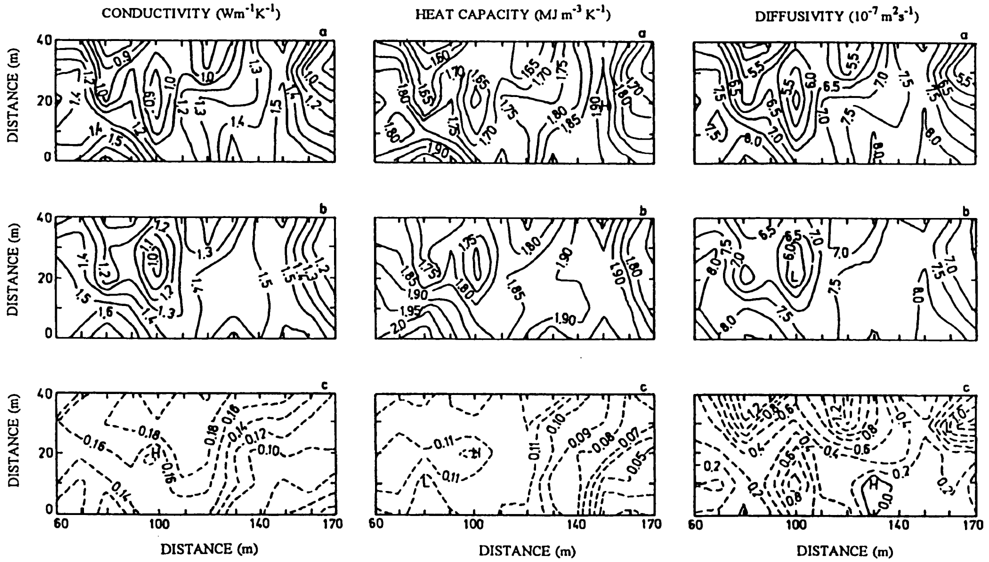

Fig. 3. Spatial distribution of topsoil thermal properties obtained on the basis of gravimetric (a) and TDR (b) measurements of soil water content and differences of these properties (c) in sugar beet field. Felin, 17 June 1992.

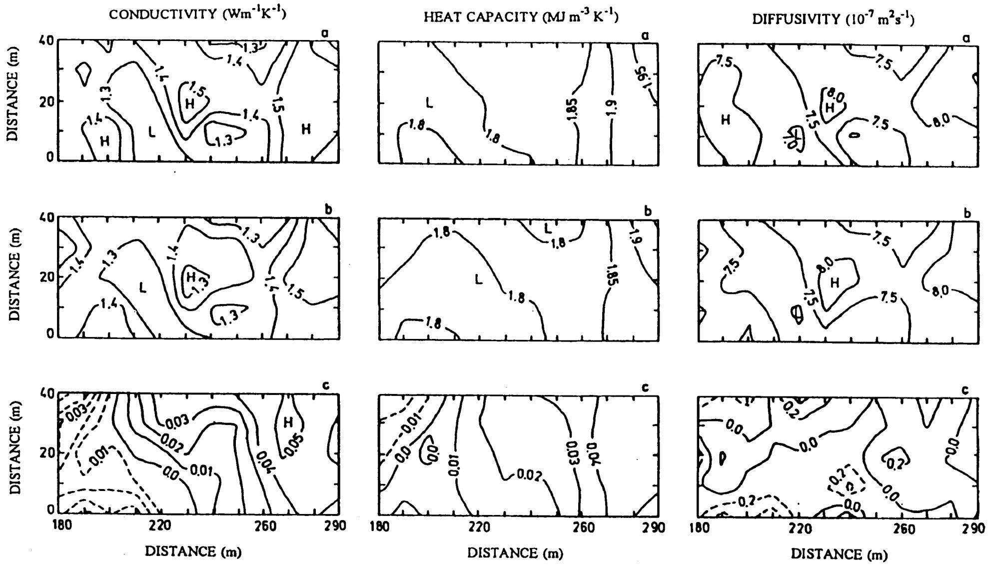

Fig. 4. Spatial distributions of topsoil thermal properties in winter wheat field on 9 July 1992. Explanations: a, b and c - as in Fig. 3.

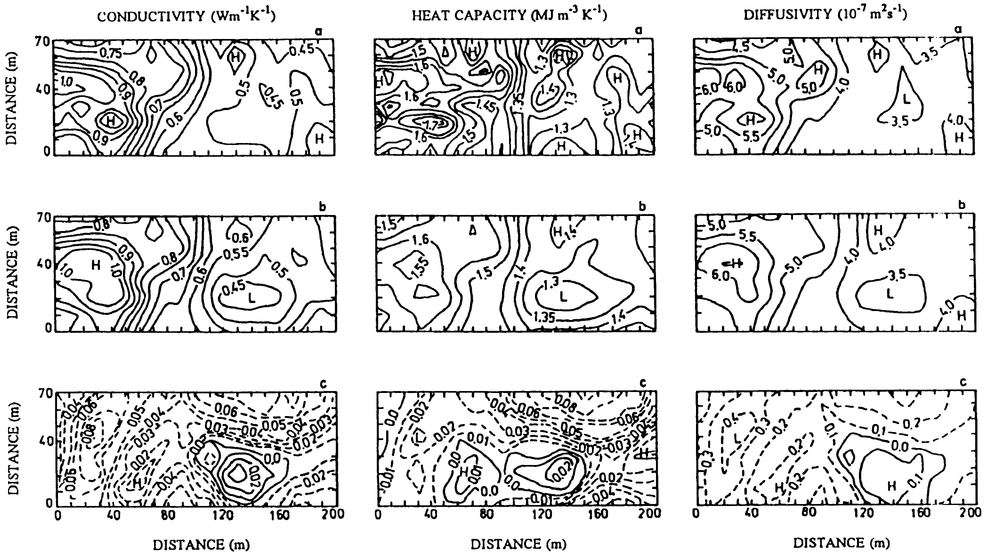

Fig. 5. Spatial distributions of topsoil thermal properties in maize and spring wheat fields on 6 July 1993. Explanations: a, b and c - as in Fig. 3.

lower sensitivity of the TDR measurement of soil water content. It must be noted here that the estimation errors in the spatial distribution of soil thermal properties in the maps enclosed were not bigger than 0.163 W m^{-1} K^{-1}, 0.155 10^6 J m^{-3} K^{-1}, 0.792 10^{-7} m^2 s^{-1} respectively, for soil thermal conductivity, heat capacity, and thermal diffusivity. In addition to that, maps of differences between the values of thermal conductivity, heat capacity and thermal diffusivity calculated on the basis of θ_{GRAV} and θ_{TDR} in the chosen crop fields (Figs 3, 4 and 5c) have been presented. Adequately to the mean values of individual soil thermal properties (Table 1) in the winter wheat field areas with higher values of thermal properties as calculated on the basis of θ_{GRAV} were dominant, whereas in the sugar beet, spring wheat, and maize fields areas with higher values of soil thermal properties as calculated on the basis of θ_{TDR} predominated.

CONCLUIONS

Comparison of the values of soil thermal properties determined on the basis of soil water content from gravimetric and reflectometric field measurements showed that their conformity is, generally, speaking satisfactory, however, not uniform in different soil moisture ranges (better in the higher range of soil moisture, and worse in lower ranges).

Differences between mean values of thermal properties calculated on the basis of soil water content measured by these two methods in individual study objects (cultivated fields) were in percentage lower than the differences in the soil water content. The scatter of values of soil thermal properties as calculated on the basis of moisture data from the TDR method in relation to the gravimetric methods were underrated or overrated, respectively, above or below some characteristic values of soil water content and soil bulk density. It results from the influence of soil compaction on the soil water content as measured by the TDR method.

Spatial distribution of soil thermal properties determined by using the water content data as obtained from the two methods showed high similarity, however, more accuracy of the picture was observed in the case of distribution of values as obtained basing on the soil moisture data from the gravimetric method points to the fact that the TDR method of measuring soil water content is less sensitive.

On the basis of the analyses conducted a general conclusion can be drawn that using soil moisture data from the TDR method of determining soil thermal properties allows for getting almost the same mean values for a given study object as the ones obtained from the gravimetric data of soil moisture (with relatively small differences in the spatial distribution of these properties). For the above reason, and also with regard to the convenience of measurement taking and immediate availability of results, as well as a possibility of collecting a large number of these measurements in a short period of time, the use of TDR method in the studies on the spatial distribution of soil moisture and thermal properties can be recommended.

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