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VARIABILITY OF MOISTURE, TEMPERATURE AND THERMAL PROPERTIES IN BARE SOIL AND IN CROP FIELD*

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A b s t r a c t. The time and space variability of soil moisture, air content, temperature, and thermal properties was measured, determined, and analysed using a TDR moisture meter, thermocouple temperature gauges, a statistical-physical model of thermal conductivity, and empirical formula for thermal capacity, as well as classical statistics and geostatistics. Input data originated from measurements of soil moisture, temperature, and density, taken at points located at various depths, and distributed over fields with and without plants. Time-spatial variability was observed for all the physical values under studied, in bare soil and in crop fields alike. Their mean values and variability were related with the plant development, mainly through the soil moisture and density, and in the case of soil temperature - through the restricted heat influx into the soil.

K e y w o r d s: time-spatial variability, soil physical properties

INTRODUCTION

By the nature of things the processes of mass and heat flow in soil are dynamic processes. This situation is due to the soil itself, as it is a dispersive multi-component medium, and to the plants and climate. Specific physical conditions of soil depend, to a considerable extent, on its physical properties [10,11]. These properties, and their variability in time and space, are in turn the result of the natural processes of soil formation under specific topographic and climatic conditions, of biological life, and of the human activity [4,8,9,12].

The objective of this study was to investigate the effect of plant cover on the time-spatial variability of the moisture, temperature, and thermal properties of soil.

OBJECT AND METHODS

The experimental plots were located at Felin, near Lublin, on an Orthic Luvisol developed from silt formations, non-uniform, over limestone. The granular composition of the cultivated horizon of the soil was as follows: 20, 48, 26 and 6 % w/w for particle sizes of 1-0.1, 0.1-0.02, 0.02-0.002, and <0.002 mm, respectively. The organic matter content was 1.5 %, the content of quartz - 67 %, and that of other minerals - 31.5 %. Solid phase density was 2.65 Mg m^{-3}. The measurements were taken during June and July, on experimental plots of 35x35 m under barley and rye, and on plots of black fallow. The plots were situated side by side. During the period of the measurements, barley passed from the sprouting phase to full ripeness, while rye from the earing phase to full ripeness.

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Soil moisture measurements within the layer of 0-0.8 m were performed in the afternoon hours, using a TDR (Time Domain Reflectometry) meter [2,3]. The TDR instrument (made by Easy Test Ltd., Lublin, Poland) was composed of a digital display, to which probes from the following layers were connected: 0-0.05, 0.10-0.15, 0.20-0.25, 0.30-0.35, 0.40-0.45, 0.50-0.55, 0.80-0.85 m. After the removal of the TDR probes, the same layers of the soil were used to take soil samples (into 100 cm^3 cylinders) to determine the moisture and density of the soil.

Soil temperature measurements in the horizon of 0-0.96 m were performed using thermocouple temperature gauges connected to an automatic data gathering system [1,5]. The thermocouples were positioned at the following depths: 0.01, 0.015, 0.02, 0.03, 0.04, 0.06, 0.08, 0.10, 0.12, 0.16, 0.20, 0.24, 0.32, 0.48, 0.64, 0.96 m. Soil temperature was measured in the barley plots and in the bare soil.

On the basis of the collected measurement data, i.e. the values of soil moisture, density, and the density of its solid phase, as well as its mineralogical composition, the thermal properties of soil were calculated for three plots, using the Soil thermal properties software package [7] based on an empirical formula for the heat capacity and thermal diffusivity, and on a statistical-physical model of the thermal conductivity of soil [6].

The time-spatial variability of the water and air content in the soil, of the thermal properties of soil, and of its temperature, was analysed by means of classical statistics (mean values, standard deviation, coefficient of variability, skewness, kurtosis) and of geostatistics (variogram, kriging) [4,9,12].

RESULTS

Statistical analysis

The time-spatial variability of the physical properties of soil was analysed taking into consideration the whole soil layer under study, as well as its individual horizons. The results of the analysis are presented in Table 1 and Fig. 1.

As can be seen from comparisons of the mean values of soil moisture in particular plots for the whole soil profile, the lowest values were recorded in the rye field, and the highest in the plot with no plant cover. The mean values of soil density in the plot with rye and in the bare soil plot were virtually the same; in the barley plot - the mean density of the soil was lower than in the bare soil plot (solid phase content - difference between one and the sum of water and air contents). The thermal properties of the soil reflected the water content in the soil, although in the case of the thermal conductivity and diffusivity of the soil the barley plot had values somewhat lower than the rye plot, even though the soil moisture in the barley plot was a little higher, but in this case the thermal conductivity and diffusivity were more strongly affected by the soil density, and this was higher in the rye plot. The heat capacity of the soil followed the distribution of soil moisture in the plots. The mean soil temperature was 0.3 °C higher in the bare soil than in the barley plot.

Considering the soil profiles in the plots (Fig. 1), it was found that the distribution of the physical properties under study, with the exception of soil temperature and air content, varied from the lowest values at the soil surface to the highest values at the lowest horizon in the case of the bare soil and the barley plots, with the bare soil plot being characterized by higher values in general. The rye plot had the highest values at the surface and the lowest values at the lowest horizon. The soil temperature was the highest on the soil surface and the lowest at the deepest horizon, the bare soil plot having higher values on the surface, at the depth of 64 cm the mean values were the same, and at deeper horizons higher soil temperature values were recorded in the plots with plant cover.

The coefficients of variability calculated for the whole profile from the individual plots were the highest in the case of moisture in the rye plot, air content and soil

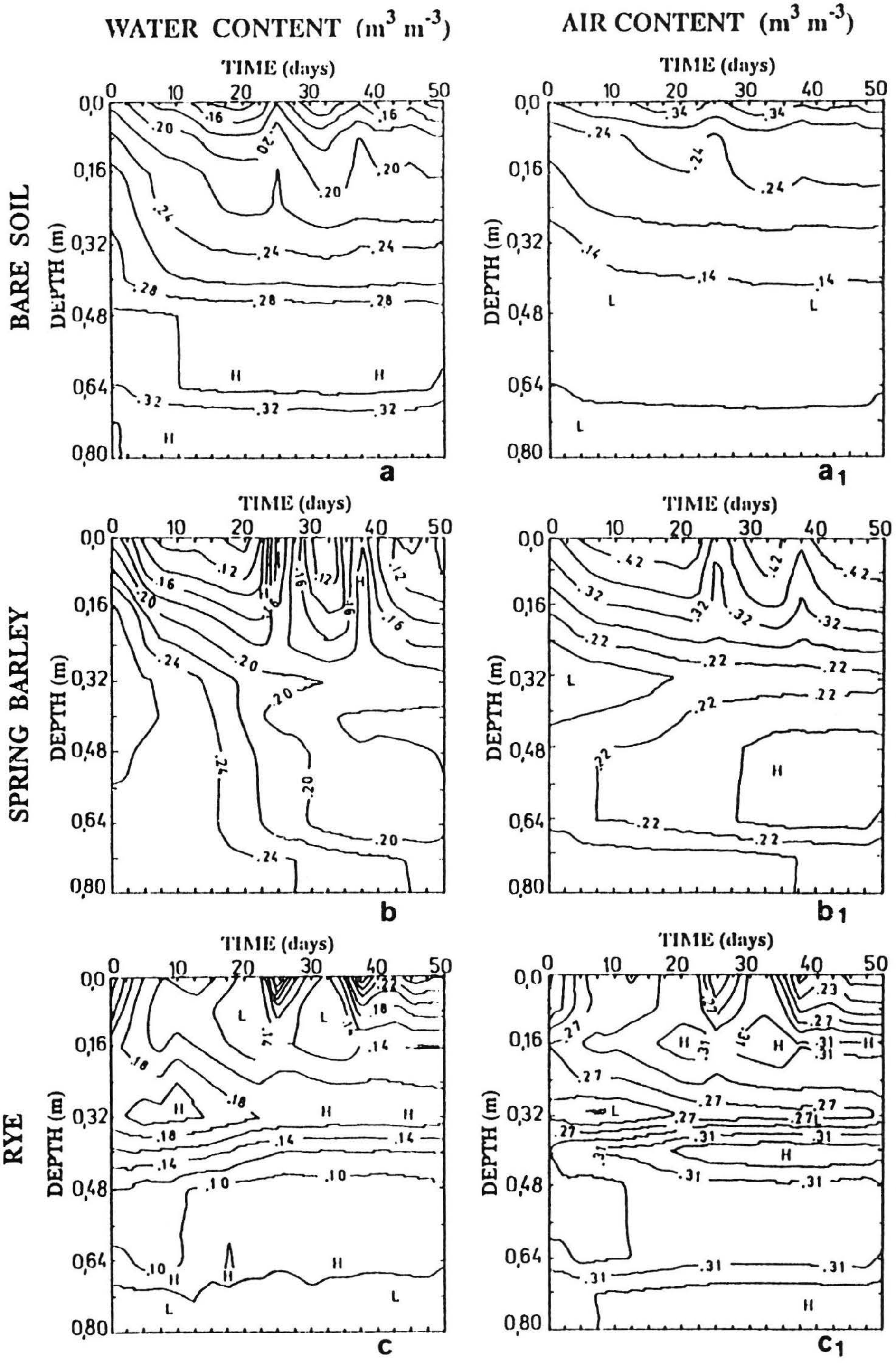

Fig. 1. Estimation maps of water content (a,b,c), air content (a_1,b_1,c_1), thermal conductivity (a_2,b_2,c_2), heat capacity (a_3,b_3,c_3), thermal diffusivity (a_4,b_4,c_4) and temperature (a_5,b_5) in the soil profile and in time, in crop fields and in bare soil.

THERMAL CONDUCTIVITY, ($W\,m^{-1}\,K^{-1}$) HEAT CAPACITY, 10^6 ($J\,m^{-3}\,K^{-1}$)

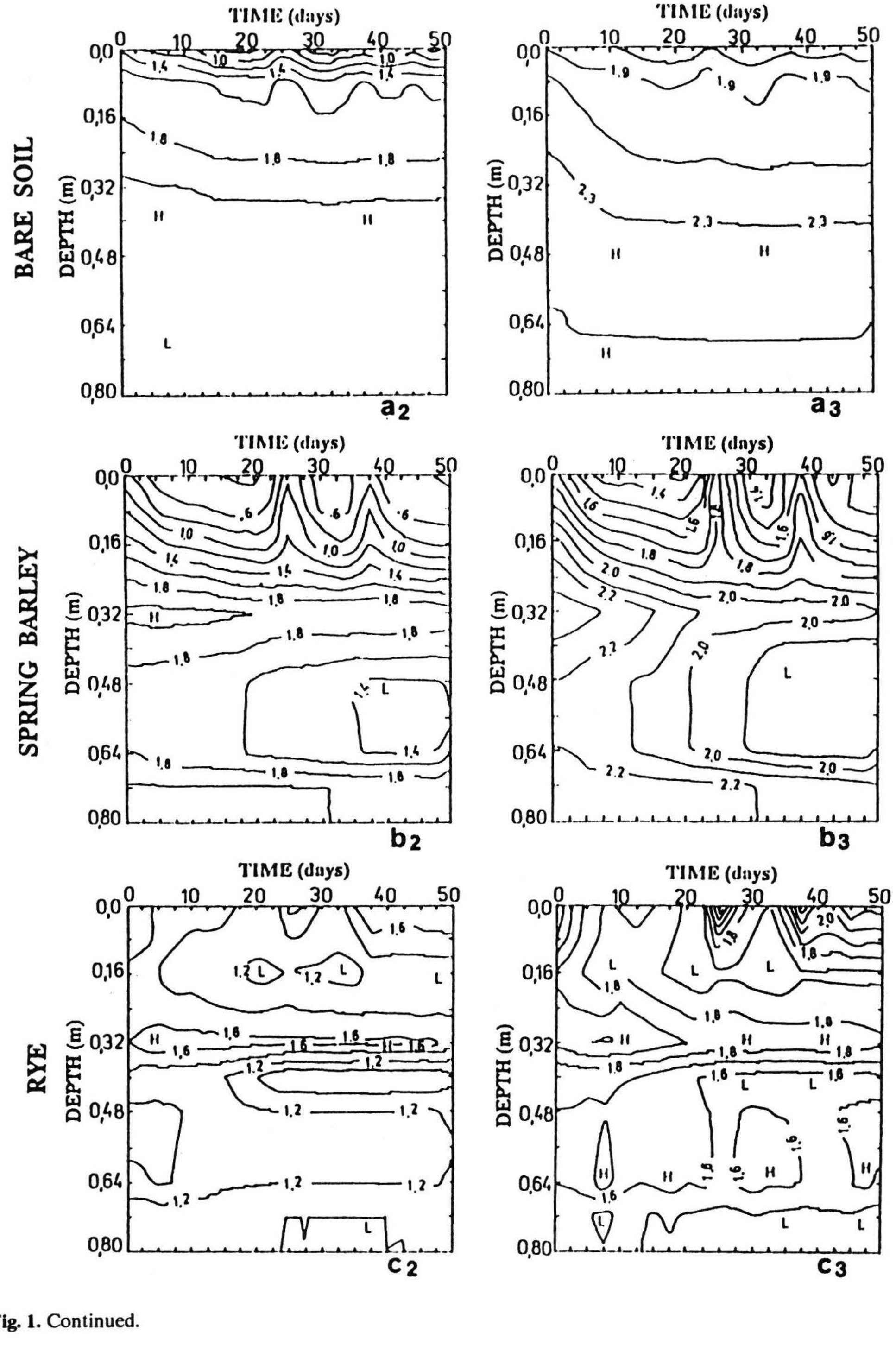

Fig. 1. Continued.

THERMAL DIFFUSIVITY, 10^{-7} (m^2 s^{-1})

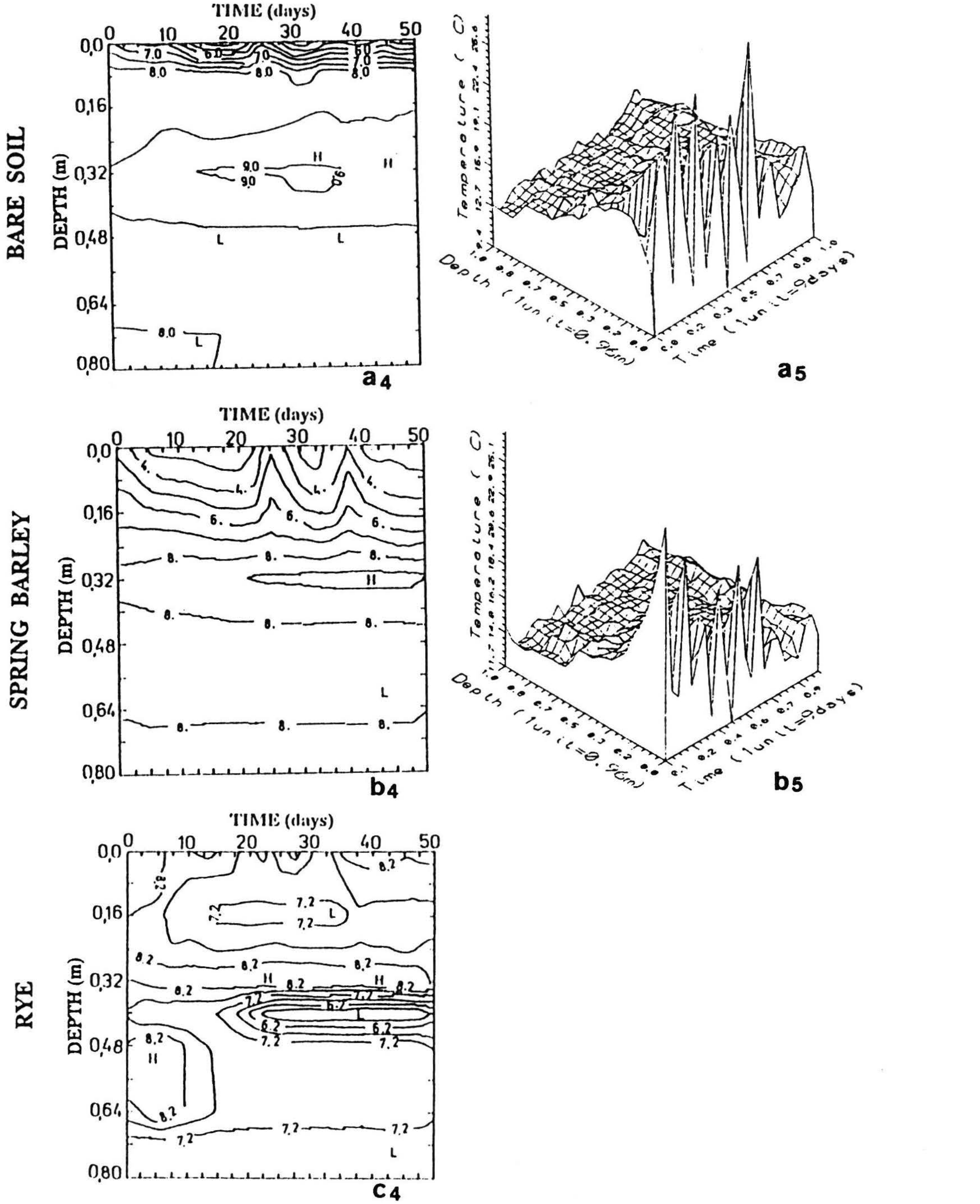

Fig. 1. Continued.

Table 1. Semivariogram parameters for water and air content, thermal conductivity, heat capacity and thermal diffusivity of bare soil and spring barley and rye fields

Property	Models of semivariograms											
	Bare soil				Spring barley				Rye			
	Type of model	Nugget	Sill	Range (unit)	Type of model	Nugget	Sill	Range (unit)	Type of model	Nugget	Sill	Range (unit)
Water $(m^3 m^{-3})^2$	Exp.	0.0	0.0017	0.3	Exp.	0.0	0.025	0.25	Guas.	0.0	0.0026	0.1
Air $(m^3 m^{-3})^2$	Exp.	0.0	0.04	0.3	Sph.	0.0	0.4	0.3	Exp.	0.0	0.0027	0.25
Conductivity $(W\ m^{-1} k^{-1})^2$	Exp.	0.0	0.165	0.3	Sph.	0.0	0.135	0.3	Exp.	0.0	0.08	0.17
Capacity $(J\ m^{-3} K^{-1})^2$	Exp.	0.0	0.045	0.35	Sph.	0.0	0.52	0.25	Guas.	0.0	0.043	0.1
Diffusivity $(m^2 s^{-1})^2$	Exp.	0.0	2.7	0.25	Sph.	0.0	2.75	0.3	Exp.	0.0	0.65	0.15

For time axis: 1 unit = 50 days
For spatial axis: 1 unit = 0.8 m

temperature in the bare soil plot, and thermal properties in the barley plot. The lowest variability was observed in the case of moisture in the bare soil plot, air content and thermal properties in the rye plot.

Considering the soil profiles, the highest variability was observed in the case of moisture, air content, thermal properties in the barley plot, and soil temperature in the bare soil plot; the lowest variability within the soil profile was observed in the case of moisture, air content, heat capacity, and thermal conductivity and diffusivity of soil in soil horizons below 0.1 m in the bare soil plot. In the case of thermal conductivity and diffusivity of soil in the 0-0.1 m layer, the lowest values were observed in the rye plot.

Analysis of the time-spatial variability

Coordinates describing the objects under study belong in the domain of time and space, and therefore the coordinates were unified and converted into relative coordinates. The time-spatial variability of soil moisture, air content, and the thermal properties for the whole profile in individual plots for a period of 50 days was studied using variograms. The values of nugget effect, thresholds, and ranges of time-spatial autocorrelation were determined, and models of variograms were matched with empirical values (Table 2). Spatial correlation was found for all the physical properties of soil studied. In most cases the form of the time-spatial relations was exponential. The highest values of the range were observed in the case of the bare soil, somewhat lower or equal to those of bare soil in the case of the barley plot, and distinctly lower in the case of the rye plot. As follows from the statistical analyses performed earlier (Table 1) and from the calculated parameters of the variograms (Table 2), the water content and bulk density of the soil have a fundamen- tal effect on the time-spatial variability and on the range of relations between the air content and the thermal properties of the soil. In the soil moisture range between the soil field water capacity and the state of full saturation, water has the decisive effect on the variability and ranges of air content in the soil and of its thermal properties; this is exemplified by the bare soil. With soil moisture levels below the field water capacity, an effect of bulk density of soil on the variability and ranges of the physical properties under study becomes apparent - this is exemplified by the plots with barley and rye.

Table 2. Summary statistics for water and air content, thermal conductivity, heat capacity, thermal diffusivity and temperature of bare soil, spring barley and rye fields

Statistics	Water content	Air content	Thermal conductivity	Heat capacity	Thermal diffusivity	Temperature
	m^3m^{-3}	m^3m^{-3}	$W\,m^{-1}K^{-1}$	$10^6J\,m^{-3}K^{-1}$	$10^{-7}m^2s^{-1}$	^oC
			Bare soil			
Mean	0.234	0.2	1.716	2.118	7.981	16.2
St. dev.	0.062	0.093	0.421	0.319	1.282	3.5
Coef. var. (%)	26.6	46.6	24.5	15.1	16.1	21.3
Skewness	-0.18	0.427	-1.395	-0.237	-2.2	1.26
Kurtosis	2.173	2.254	4.092	2.152	6.904	4.604
			Spring barley			
Mean	0.183	0.292	1.292	1.822	6.709	15.9
St. dev.	0.054	0.105	0.606	0.321	2.36	2.4
Coef. var. (%)	29.3	36.1	46.9	17.6	35.2	14.8
Skewness	-0.192	0.153	-0.24	-0.221	-0.417	1.387
Kurtosis	1.345	1.706	1.537	1.762	1.651	5.26
			Rye			
Mean	0.145	0.29	1.329	1.743	7.546	
St. dev.	0.054	0.047	0.3	0.204	0.982	
Coef. var. (%)	37.4	16.1	22.6	11.7	13.0	-
Skewness	0.395	-0.891	0.101	0.765	-0.657	
Kurtosis	2.542	3.271	1.86	3.029	2.901	

Estimated maps of soil water and air content, soil temperature and thermal properties

Using the models of variograms, as well as the optimum interpolation method of kriging, the authors reproduced the fields of water and air content, and of thermal properties in the soil profile, over a period of 50 days, and of soil temperature over the first 9 days (Fig. 1). These maps illustrate the dynamics of the physical properties of soil under study, and fully reflect water consumption by plants and water losses for evaporation from the surface of the soil. The changing water content in the soil (Fig. 1a, b, c) causes a change in the thermal properties of the soil (Fig. 1a_2, a_3, a_4, b_2, b_3, b_4, c_2, c_3, c_4), which in turn affects the temperature distribution in the soil (Fig. 1a_5, b_5). It can be concluded from the figures that water is taken by plants (plant root systems) from various places, depending on the stage of plant development. Rye, which was grown (earing phase), was already through consuming water from the deeper horizons and continued to thrive on water from precipitation for its further development. This is shown by the strong dynamics of water in the surface horizon, and stabilized moisture at deeper horizons. Barley, which had passed through all its growth stages, used the water from the surface horizon, and then, as its root system developed, the water from the deeper horizons. Strong moisture dynamics was observed throughout the profile studied. Over the whole period of the study, the bare soil plot did not indicate any stronger dynamics of the physical properties under study, and, as one can see, the distribution of values within the profile stabilized with time and no considerable changes occurred during that period, even following precipitations. Fig. 1a_5, b_5 show the dynamics of soil temperature in the bare soil plot and in the barley plot. A stronger dynamics of soil temperature characterized the bare soil plot, a weaker one the barley plot. The process of mulching by plants was responsible for the weaker soil temperature dynamics in the barley plot.

CONCLUSIONS

The time-spatial variability of soil moisture in the soil profile showed considerable differences between the bare soil and the soil with plant cover. From the differentiation in the soil water content in these plots, the water consumption rate by plant root systems can be estimated, as a function of depth and time.

The variability of air content, thermal conductivity, heat capacity and thermal diffusivity in time and depth (space) is significantly different in the bare soil, as compared to soil covered with plants. Such differences were mainly due to the soil water content and the changing bulk density in the soil profile.

The bare soil was characterized by a higher temperature time-spatial variability than the crop field in the top soil horizons; the deeper horizons showed smaller differentiation and variability in time.

The time-spatial correlation of the physical properties under study through the soil profile and time was determined. The correlation range of the properties changed with changes in the soil moisture level.

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