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SPATIAL DISTRIBUTION OF TOPSOIL THERMAL PROPERTIES IN FIELD WITHOUT CROPS

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Abstract. The paper has been based on the results of the measures of soil moisture and density in 1-5 cm layer (soil without crops) as well as the values of thermal properties found from the statistical - physical model of thermal conductivity and from the mathematical formula for heat capacity and thermal diffusivity. The data were derived from the fields with old- and fresh-cultivated soil. Measure points were placed in the knots of a net of squares with 5 m sides and covered an area of 20x40 m. The analysis of spatial variability of the investigated physical values of soil was carried out using the methods of classic statistics and geostatistics. The smallest variability was found in heat capacity, while the greatest one was found in thermal conductivity of soil. Differentiation of the moisture of soil in the field showed greater influence on the variability of thermal conductivity and diffusivity than the differentiation of the density of soil. In the case of heat capacity, moisture had the major influence on capacity values, however, the density variation on the field had greater influence on variability of heat capacity of soil. The lack of real spatial relationship of different physical properties of compacted soil was observed. In fresh - cultivated soil this relationship was observed within the range of about 8 m.

Keywords: spatial variability, thermal properties of soil

INTRODUCTION

The research of the temperature field in soil can be carried out directly through soil temperature measurement and analysis of data using statistic and stochastic methods, as well as investigating the processes of mass and energy transport in soil [15]. The rate of energy transport in soil depends on its thermal properties, which are determined by the structure state, type of soil and water content [11,12, 14,16,19]. A knowledge of the thermal properties of soil is necessary to estimate the effects of thermal amelioration, land reclamation or agrotechnical amelioration, i.e., to estimate these measures in terms of their influence on the thermal condition of soil, or to search for the way to use thermal effects to control and regulate the water-thermal relations. The fact that the energy exchange takes place on the active surface of soil, as well as the fact that the arable layer is the most dynamic layer during plant vegetation period, both decide that investigating the changes of physical properties of this layer of soil is important not only in terms of modelling the mass and energy exchange in surface layer of the atmosphere and soil, but also in terms of describing the soil by soil scientists as well as cultivating it by agrotechnicians [1,2,4-7,9,16-18]. This kind of research allows us to get to know and understand investigated processes better. The results of the research can be a good base for working on the optimum methods of controlling and regulating the water-thermal-air relations with plant environment as well as effective use of mass and energy.

The purpose of the paper is to investigate the spatial thermal properties of soil; to estimate their variability on the field with compacted soil and loose soil (fresh cultivated); as well as to get a picture of the distribution of soil properties within the research object, using methods of classic statistics and geostatistics (variogram, kriging).

OBJECT AND METHODS

The studied object was a field of the Experimental Station of the Institute of Natural Resources and Agrobiology in Caria del Rio, n/Seville, Spain (soil developed in dry climate -Xerochrept). The necessary data for calculating the thermal properties, concerning soil moisture and density in surface layer (1-5 cm), was received from the measures of the field with compacted and fresh cultivated soil (ploughing and harrowing) in November 1993. Measuring points were placed in knots of a net of squares with 5 m sides. These points covered an area of 20x40 m (Fig. 1). Soil density and moisture were estimated using the gravimetric method. Soil samples were taken into 201 cm^3 cylinders (diameter 8 cm, height 4 cm). Despite very little distance between the fields (about 100 m) it appeared that the investigated soil granulometric compositions was different. The first one (compacted) contained 77.6 % of sand, 8.9 % of silt, 13.5 % of clay, and 0.9 % of organic matter. The second one (loose) contained 56.6 % of sand, 18.6 % of silt, 24.8 % of clay, and 0.9 % of organic matter. In calculations of thermal properties of soil, the mineral composition of soil main components should be considered. The content of quartz and other minerals was estimated using the granulometric composition, assuming that the sand fraction contained mainly quartz, while silt and clay fractions contained other minerals. The density of the solid phase of the investigated soils was 2.65 Mg m^{-3}, and the density of organic matter of 1.3 Mg m^{-3} was taken from literature [14]. Taking this data into consideration the content of quartz, other minerals and organic matter in volume unit for these soils was found. The compacted soil contained 77.6 % of quartz, 21.6 % of other minerals, and 1.8 % of organic matter. Loose soil contained 56 % of quartz, 42.2 % of other minerals, and 1.8 % of organic matter. The temperature of the soil in the whole investigated layer was assumed equal for both fields 20 °C. To estimate the thermal properties of soil, the empiric formula for heat volume and statistical-physical model for thermal conductivity of soil were used.

Volumetric heat capacity - C ($Jm^{-3}K^{-1}$) was found using the following formula [14]:

$$C = (2.0x_m + 2.51x_o + 4.19\,\theta_v)\,10^6$$

where x_m, x_o, θ_v(m^3 m^{-3}) - the content of mineral and organic particles and water in soil volume unit.

The statistical-physical model of soil thermal conductivity has been built on the base of heat resistance of soil components and statistic dependence (polynomial distribution), allowing to find the possibility of the appearance of all possible configurations of particles (resistors) participating in conduction [11]. According to the model, the mean value of soil thermal conductivity - λ($Wm^{-1}K^{-1}$) is calculated from the following equation:

$$\lambda = \frac{4\pi}{u\sum_{j=1}^{L}\dfrac{P\,(x_{1j}, x_{2j}, \ldots, x_{kj})}{x_{1j}\,\lambda\,(T)_1\, r_1 + \ldots + x_{kj}\,\lambda(T)_k\, r_k}}$$

where u - the number of parallel contacts of soil particles considered thermal resistors, L - number of all possible combinations of particle placement, x_{ij} - number of particles of the specific component, λ_i - thermal conductivity of different soil components, T(°C) - soil temperature, r_i - equivalent radii of soil particles treated as spheres, P - possibility of appearance of a specific combination of soil particles found from polynomial distribution:

$$P(x_{1j}, x_{2j}, \ldots, x_{kj}) = \frac{u!}{x_{1j}!\, x_{2j}! \ldots x_{kj}!} f_1^{x_{1j}} f_2^{x_{2j}} \ldots f_k^{x_{kj}}$$

where

$$\sum_{j=1}^{L} P(x_{ij}) = 1, \quad \sum_{i=1}^{k} x_{ij} = u, j = 1,2,\ldots,L.$$

This equation gives us the possibility of u number of independent attempts receiving exactly x_{ij} number of results of type j, if the possibility of getting the i result in a single trial is f_i, i=1,2,...,k. In our case $f_1 f_2,\ldots,f_k$ are contents of different minerals, organic matter, water and air in the volume unit and they are treated as possibilities of receiving the i type of result in a single trial.

The model modifies the number of parallel connections of u particles along with the change of soil saturation with water θ_v/Φ (where: θ_v (m^3m^{-3}) - water content in volume unit of soil, Φ (m^3m^{-3}) - total porosity of soil) and adds up the radii of particle spheres, depending on the soil type (mineral soils - 0.044, organic soils - 0.08). Mean square error while estimating the volume of thermal conductivity using this model for similar soils was about 0.09 $Wm^{-1}K^{-1}$ [13].

Thermal diffusivity of soil - α (m^2s^{-1}) was found as a proportion of the thermal conductivity and volumetric heat capacity:

$$\alpha = \frac{\lambda}{C_v}.$$

Spatial variability of moisture, density, air content, and thermal properties of the soil were analysed using classic statistics (mean and extreme values, standard deviation, variability coefficient, curtosis and skewness) and geostatistics (variogram, kriging). Basing on the data of different properties of soil, first checking their stationary, semivariation values and dimensions - γ (dimension)^2 were found for these properties according to the following formula [18]:

$$\gamma(h) = \frac{1}{2N_h} \sum_{i=1}^{N_h} [(f(x_i + h) - f(x_i)]^2$$

where N_h is the number of pairs of points away from each other by $h, f(x_i)$ - measured value of the point x_i, x_i - spatial coordinate. The value of 2 γ (h) is the estimation of dispersions of measured values at the points away from each other by h. Mathematic models are matched with chosen semivariograms. These models are later used to estimate the area of investigated physical values using the kriging method.

Kriging, one of the best methods of estimating the area of a specific physical value in the optimal way, works on the base of the assumption of linear dependence of the unknown estimator f^* on the given parameter f on the value of the parameter at various points [18]:

$$f^*(x_i) = \sum_{i=1}^{N} a_i f(x_i)$$

where a_i - weight coefficient matched with x_i, N - number of measure points, $f(x_i)$ - measured value at the point x_i. The values of a_i are found after considering the non-weighed conditions of the estimator f^* (expected value of the f^* value differences and the measured f equals zero) and its effectivity (variation of differences of f^* and f has minimum value) from the following system of equations:

$$\sum_{j=1}^{N} a_j \gamma(x_i, x_j) + \mu = \gamma(x_i, x_o) \quad i = 1,2,\ldots,n$$

$$\sum_{j=1}^{N} a_j = 1$$

where $\gamma(x_i - x_j)$ - semivariation for the distance between points x_i and x_j, $\gamma(x_i - x_o)$ - semivariation for the point x_i and the interpolated point

x_o, μ - Lagrange's multiplicator. Measured weight coefficients and Lagrange's multiplicator will allow to estimate the area of the given physical value and the minimum estimation variation - $\sigma_k{}^2$ (kriging variance) from the following formula:

$$\sigma_k^2=\mu+\sum_{j=1}^{N} a_j\,\gamma(x_i,x_o)\,.$$

During estimating the values of thermal conductivity of soil, calculating the variograms and estimating the distribution of physical values on the objects of research, Soil Thermal Properties Software Package and GEO-EAS [3,10] computer programs were used. The relative number of measured data for describing the physical properties of soil on the investigated objects using the statistic and geostatistic analysis was estimated on the base of the results included in the papers of McBrotney and Webster [8], Webster and Burgess [17] and Brus [2].

RESULTS

The data displayed in Table 1 shows that the greatest mean values have been observed for the density, air-content, conductivity and thermal diffusivity of soil on the field with compacted soil, and for the moisture and air-volume on the field with loose soil. The mean density of compacted soil was 8.7 % (0.119 Mg m^{-3}) greater than in loose soil, while moisture was 26.5 % (0.054 m^{3}m^{-3}) smaller. Observed differences in the moisture of the soil between the fields was caused by different sorptivity of the water in the investigated soil (different granulometric composition). Greater density and quartz content (about 22 %) in compacted soil decided that the mean values of conductivity and thermal diffusivity were 19.7 % and 28 % greater than in loose soil. Heat capacity of the compacted soil was 7.1 % smaller than in loose soil. In this case mainly the moisture of the soil stimulated such composition.

The distribution of thermal conductivity and diffusivity was caused mainly by moisture, and it decreased along with the increase of moisture. The distribution of the heat capacity of the soil depended on soil density and increased along with the increase of density differentiation. From 2.8 % to 14 % higher values of standard deviation have been observed for density, moisture, air-content, and heat capacity of the soil on the field with loose soil, while in compacted soil - 52.4 % higher

T a b l e 1. Summary statistics for bulk density, water and air content, thermal conductivity, heat capacity and thermal diffusivity of bare soil. N - number of measuring points

Statistics (N=45)	Bulk density (Mgm$^{-3)}$	Water content	Air content	Thermal conductivity (Wm^{-1}K^{-1})	Heat capacity (Jm^{-3}K^{-1})	Thermal diffusivity (m^{2}s^{-1})
		(m3m^{-3})				
			Compacted soil			
Mean	1.493	0.15	0.286	1.52	1.764	8.454
St. dev.	0.108	0.023	0.057	0.471	0.157	1.991
Coef. var. (%)	7.2	15.4	19.7	31.0	8.9	23.6
Skewness	0.245	-0.092	-0.146	-0.106	0.032	-0.397
Kurtosis	2.463	2.23	2.3	2.079	2.194	2.212
Minimum	1.315	0.102	0.166	0.631	1.456	4.332
Maximum	1.742	0.197	0.394	2.366	2.082	11.640
			Loose soil			
Mean	1.374	0.204	0.278	1.270	1.898	6.607
St. dev.	0.111	0.025	0.063	0.309	0.179	1.018
Coef. var. (%)	8.1	12.3	22.8	24.3	9.4	15.4
Skewness	0.599	0.343	-0.576	0.288	0.534	-0.184
Kurtosis	3.474	2.208	2.757	2.356	2.467	2.235
Minimum	1.150	0.163	0.116	0.727	1.619	4.197
Maximum	1.690	0.263	0.382	1.991	2.315	8.600

Table 2. Semivariogram parameters for bulk density, water and air content, thermal conductivity, heat capacity and thermal diffusivity of bare soil

Property	Unit	Nugget	Sill	Range	Model
			Compacted soil		
Bulk density	Mgm^{-3}	0.012	-	-	linear
Water content	m^3m^{-3}	0.0004	0.00025	24	linear
Air content	m^3m^{-3}	0.0033	-	-	linear
Thermal conduc.	$Wm^{-1}K^{-1}$	0.235	-	-	linear
Heat capacity	$10^{12}\ Jm^{-3}K^{-1}$	0.0255	-	-	linear
Thermal diffusiv.	$10^{-14}\ m^2s^{-1}$	4.1	-	-	linear
			Loose soil		
Bulk density	Mgm^{-3}	0.0	0.0138	8	spherical
Water content	m^3m^{-3}	0.0	0.0006	7.5	spherical
Air content	m^3m^{-3}	0.0	0.0042	8	spherical
Thermal conduc.	$Wm^{-1}K^{-1}$	0.0	0.098	8	spherical
Heat capacity	$10^{12}\ Jm^{-3}K^{-1}$	0.0	0.0325	8	spherical
Thermal diffusiv.	$10^{-14}\ m^2s^{-1}$	0.0	1.1	8	spherical

values for conductivity and 95.4 % higher values for thermal diffusivity on the field with compacted soil.

The smallest variability among soil thermal properties was observed for heat capacity - 8.9 %. The greatest variability was recorded for soil thermal conductivity - 31 %. Water content in soil and its differentiation have had greater influence on thermal conductivity and diffusivity of the soil than the differentiation of soil density. Compacted soil showed 27.6 % and 53 % higher variability in thermal conductivity and diffusivity than loose soil. Soil moisture had major influence on the value of heat capacity, but the differentiation of density on the field had greater influence on the differentiation of soil heat capacity. Compacted soil showed 5.3 % smaller variability of heat capacity than loose soil. Chosen parameter and semivariogram models (Table 2) and their analysis allowed us to state that there is a lack of spatial relationship between the investigated physical values in compacted soil, there was a nugget effect (except moisture, where an insignificant linear relation was observed) almost everywhere, while in loose soil spatial relationship (spheric) was observed in all investigated values, with correlation range about 8 m. These observations and our earlier research [1,12] indicate that soil, which for a long time has not been cultivated and has naturally stabilized its structure, shows the tendency to develop a spatial relationship of its physical properties, like the clear nugget effect. When a spatial relationship is not observed (compacted soil), then mean values and

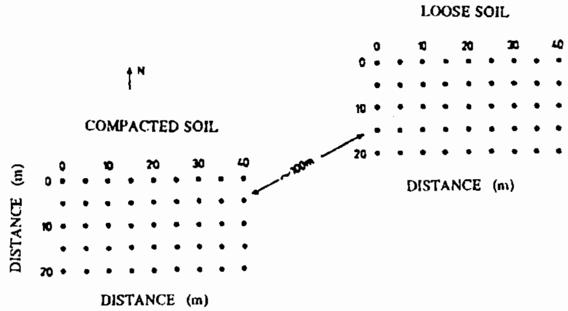
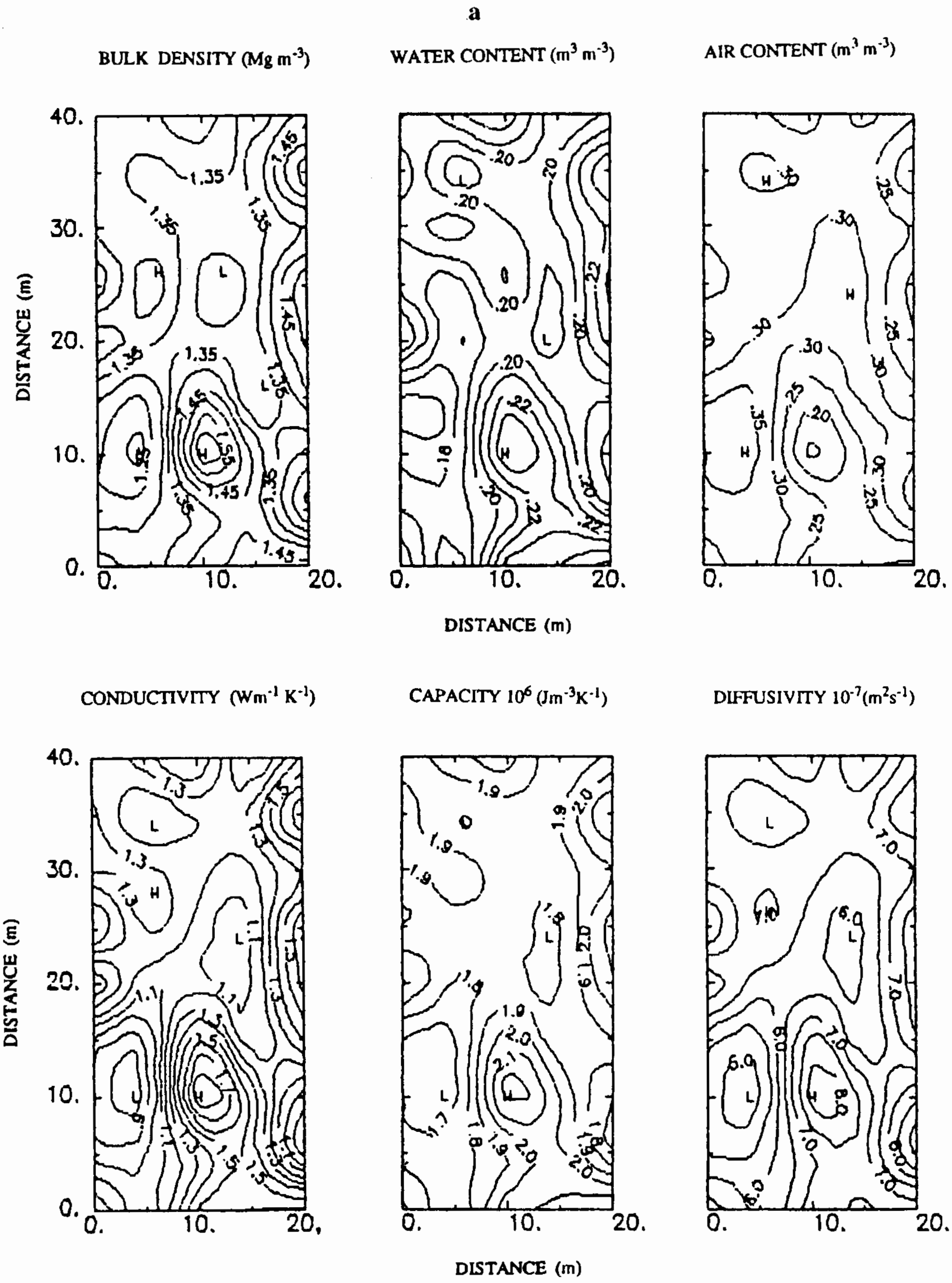


Fig. 1. Plan of the research object and the measuring points on Caria del Rio fields, n/ Seville, Spain.



a

BULK DENSITY (Mg m^{-3})

WATER CONTENT (m^3 m^{-3})

AIR CONTENT (m^3 m^{-3})

CONDUCTIVITY (Wm^{-1} K^{-1})

CAPACITY 10^6 (Jm^{-3}K^{-1})

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

Fig. 2. Maps of the values of physical properties of soil estimated using the kriging method, on the arable field without crops for compacted (a) and loose (b) soils. Explanations: H - greater than; L - smaller than.

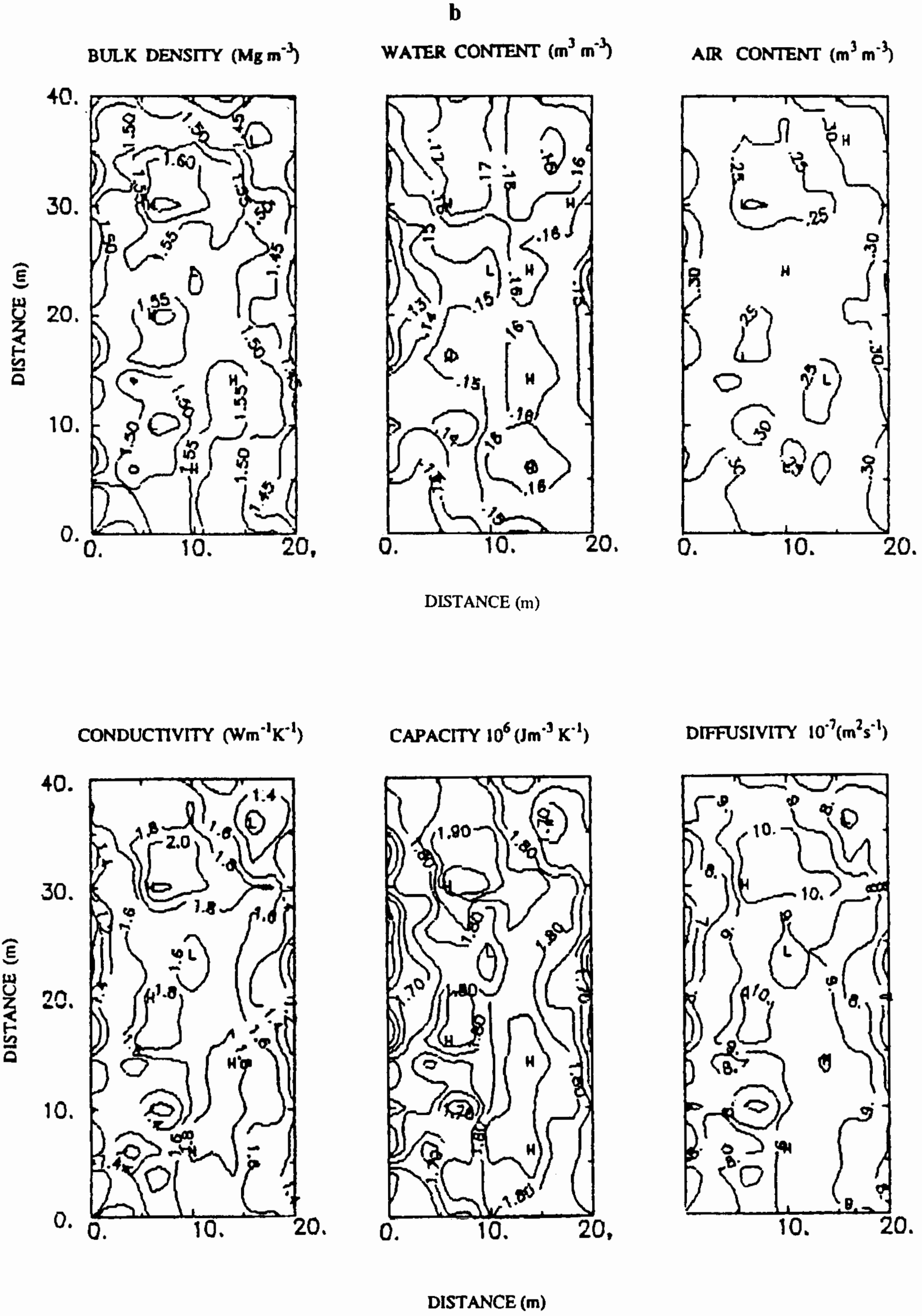


Fig. 2. Continuation.

variance (keeping the specific number of resampling according to the statistic method) are enough for a representative description of different thermal values of soil. If a spatial relationship is observed, besides average values and variance, the functions of spatial autocorrelation should also be given - for example: loose soil (Tables 1 and 2).

Parameters and semivariogram models chosen for specific physical properties of soil, as well as measured data at particular measuring points, have been used in the kriging method to estimate and sketch the maps of spatial distribution of investigated properties within the net of measure points (Fig. 2) as well as to find the estimation error value. Maps indicate that the distribution of physical properties on the field with compacted soil is irregular and these properties are not in order. However, on the field with loose soil they are regular, and equally distributed. Estimation errors of physical property values were the smallest near the measuring points (up to 5 %), while the greatest error values were in places far away from the measure points (up to 10 %). This visualization of the area of the values of soil properties and error values allows to point out the spaces on the field, where the number of samples in further measures should be either diminished or increased, so that the received picture of investigated value is estimated with an error not greater than the error assumed by the experimentator.

CONCLUSIONS

The presented results indicate that thermal properties of soil without plants can significantly change in space, they also show the different spatial relationships, which also indicates that point measures, for example of the heat stream or temperature in soil cannot be related to the whole field (they often are), but only to the nearest environment of the point. Great care while doing such research is therefore suggested. First of all it is suggested to carry the research of spatial variability of physical values of soil, which are important for heat flow, and then to consider them while estimating the thermal balance of active surface or while modelling the heat flow in soil.

An attempt used in this paper to find the thermal properties of soil and analyse the spatial variability includes the different possibilities of the physical condition of soil in the given time and place, allows to find and estimate the spatial correlation, as well as to get the optimal picture of the distribution of the value of the given parameter in space and its extrapolation with the assumed estimation error.

NOTE

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PRZESTRZENNY ROZKŁAD CIEPLNYCH WŁAŚCIWOŚCI POWIERZCHNIOWEJ WARSTWY GLEBY NA POLU BEZ ROŚLIN

Opracowanie oparto na wynikach pomiarów wilgotności i gęstości gleby w warstwie 1-5 cm (gleby bez roślin) oraz o wartości cieplnych właściwości wyznaczonych ze statystyczno-fizycznego modelu przewodnictwa cieplnego i z matematycznej formuły na pojemność i dyfuzyjność cieplną. Dane pochodziły z poletek, o uleżałej i świeżo uprawionej glebie. Punkty pomiarowe umieszczone były w węzłach siatki kwadratów o boku 5 m i obejmowały powierzchnię 20x40 m. Analizę zmienności przestrzennej badanych wielkości fizycznych gleby dokonano przy zastosowaniu metod statystyki klasycznej i geostatystyki. Najmniejszą zmienność spośród właściwości cieplnych gleby zaobserwowano dla pojemności cieplnej, największą zaś dla przewodnictwa cieplnego gleby. Zróżnicowanie wilgotności gleby na polu wykazywało większy wpływ na zmienność przewodnictwa i dyfuzyjności cieplnej niż zróżnicowanie jej gęstości. W przypadku pojemności cieplnej, wilgotność miała zasadniczy wpływ na wartości pojemności, na jej zmienność większy wpływ miało jednak zróżnicowanie gęstości na polu. Zaobserwowano brak wyraźnej przestrzennej zależności dla poszczególnych właściwości fizycznych gleby w przypadku gleby uleżałej, natomiast dla gleby świeżo uprawionej obserwowano tę zależność z zakresem około 8 m.

Słowa kluczowe: przestrzenna zmienność, cieplne właściwości gleby