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ORIGINAL PAPER

SPATIAL VARIABILITY OF WATER PROPERTIES OF SOILS FORMED FROM GLACIOLIMNIC DEPOSITS IN SĘPOPOL LOWLAND (POLAND) – RESULTS FROM A FIELD-SCALE STUDY*

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Abstract

Soil water properties are one of the most important soil features which determine water distribution and its availability for plants. Therefore, the aim of the study was to describe selected soil air-water properties and assess the size of spatial autocorrelation for soil properties. The soil samples were collected from a two-hectare field located in the mesoregion called Sępopol Lowland, in north-eastern Poland. The area is covered with Eutric Gleyic Cambisols formed from glaciolimnic sediments. Soil water retention properties as well as bulk and specific densities were analysed. The following soil pores and soil water capacities were calculated: macropores, mesopores, micropores, potential useful water retention (AWC – available water capacity), and among AWC, readily available water capacity (RAWC), and small pores available water capacity (SAWC). Geostatistical analyses as a function of the semivariogram and correlogram were carried out using Isatis Geovariance. The shares of the macro-, meso- and micropores in total porosity were similar. The lack of autocorrelation in the case of mesopores and micropores was noted. However, small autocorrelation was found in the case of SAWC, which was confirmed by a small nugget effect.

Keywords: Cambisols, soil water retention, water capacity, glaciolimnic deposit, spatial structure.

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INTRODUCTION

For centuries, the farmers have been noticing the variability of yields between fields, and taking account of the variability of soils occurring within the field, which did not require great effort on small areas (Zhang et al. 2002). However, the increase of a field size, as well as growing environmental and consumer requirements, made the management within a field more complex. Modern techniques of monitoring, transmutation and analysis of large sets of data, obtained from the studies within a field, enabled the management (quality of crops and yields) with regard to spatial variability of many factors, including soil properties, which are the basis for precision agriculture (Stafford 2000, Chen et al. 2015). Analyses of variability are supported by geostatistical methods, which allow the development of models that visualize the scope of changes occurring in a considered area (Zhang et al. 2011, Kumhalova, Moudry 2014, Azuka, Igué 2020).

Observations of Matheron (1963) became the basis for such models. The author stated that features of adjacent objects are more similar than those of distant ones. This phenomenon can result in the formation of spatial regions with similar values of a random variable. Water is one of the most important factors determining yields in agriculture. Therefore, the determination of the variability of factors responsible for its distribution and availability becomes extremely important (Schmidt, Presson 2003). One of these factors is soil water retention which, as a result of a multitude of factors influencing its amounts, may exhibit large spatial variability in a field scale. An important factor having an impact on the variability of field water capacity and water available to plants is the soil texture, which is not homogenous at every part of the field (Iqbal et al. 2005). This is particularly evident in young glacial landscape with varied relief and diverse soil cover. North-eastern Poland differs from the rest of the country in terms of geological deposits, soil cover, climate, vegetation, and history (Kondracki 2000). As an area of varied relief and soil cover, it is suitable for spatial variability assessments. In this area, intensive agricultural activity occurs in large-scale farms, which are increasingly often implementing precision agriculture technologies. Because of high variability of the soil parent materials and types of soils (Frielinghaus, Schmidt 1991), the use of these technologies requires research designed to determine spatial correlation of soil properties and their range within the field.

The purpose of the research was to estimate the size of spatial correlation of selected water-air properties, and to determine a semivariogram model describing the variability of studied properties within a field.

MATERIALS AND METHODS

A field of 2 hectares chosen for the research was located in Budniki village (54°11′23.3″ N, 20°38′57.5″ E), about 9 km from Lidzbark Warminski, in the mesoregion of Sępopol Lowland. Glacial till and fine-grained glaciolimnic sediments of silt texture, deposited during Vistulian Glaciation, prevail in this area (Gotkiewicz, Smołucha 1996). Mainly Vertisols, black earths, Cambisols and Luvisols were formed from these deposits. The studied area is slightly undulating land without signs of erosional processes, and the soils were classified as Eutric Gleyic Cambisols (Orzechowski et al. 2018, 2020).

The study sites were located in a square grid of 40 m x 40 m. The coordinates of 20 study sites within the study area were determined with a Magellan 20 GPS receiver. At these sites, disturbed soil samples from the topsoil humus horizon (Ap) of 0-20 cm were collected to plastic bags. In the laboratory, the soil samples were air-dried and sieved through a ø 2 mm sieve. In the earth fractions (∅ smaller than 2 mm), the following analyses were carried out: texture by the hydrometer method of Bouyoucos modified by Casagrande and Prószyński (the aerometric method), organic carbon (OC) content using a VarioMax Cube CN dry combustion analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany), specific density (Sw) by the pycnometric method. The content of anions in soil was determined by an ion chromatography technique (881 Compact IC Pro, Metrohm, Switzerland) after extraction with deionized water (soil water ratio 1:5) – Zissimos et al. (2014).

For the determination of bulk density (So) and water retention properties, the soil samples with the intact structure are required. Therefore, soil samples from 20 sampling points were collected to 100 cm^3 Kopecky cylinders with four replications. Soil water retention properties were determined using low-pressure (in pF range 0-2.7) and high-pressure chambers (in pF range 3.0-4.2). Water capacities (W%, v/v.) were examined at the value of soil water potential at 98.1 hPa (pF 2.0), 490.5 hPa (pF 2.7), 981.0 hPa (pF 3.0) and 15 547.9 hPa (pF 4.2) – Walczak et al. (2002). The pF value, which is dimensionless, is defined as the decimal logarithm of the amount of soil water tension given measured in centimetres of the water column, corresponding to the pressure (hPa) at which water is retained in the soil (Tuller, Or 2004). Total porosity (Tp) was calculated according to the equation: $TP = (Sw - So) \times Sw^{-1} \times 100$ (%, v/v). The following volume of soil pores and the soil water capacities were calculated: macropores (TP – W%, v/v at pF 2.0), micropores (W%, v/v at pF 4.2) mesopores corresponding to potential useful water retention (AWC – available water capacity) (W%, v/v at pF 2.0 – W%, v/v at pF 4.2). Among AWC, readily available water capacity (RAWC) (W%, v/v at pF 2.0 – W%, v/v at pF 3.0), and small pores available water capacity (SAWC) (W%, v/v at pF 3.0 – W%, v/v at pF 4.2) were calculated.

Statistical analyses was performed using Statistica 10.0 software (StatSoft Inc., Tulsa, USA), and comprised the calculation of arithmetic mean (M), geometric mean (GM), median (Me), coefficient of variation (CV), skewness (Sk) and kurtosis (K). The Shapiro-Wilk normality test was also carried out. The Moran index was calculated using ArcGis 9.3. Geostatistical analysis as a function of the semivariogram, and a correlogram was drawn using Isatis geostatistical software (Geovariance Co., Avon-Fountainebleau, France).

RESULTS AND DISCUSSION

The literature presents many views on the origin of the stagnation and of clays in the Sępopol Lowland. Some German geologists claimed that the presence of inertia in the East-Masurian area at highly different levels, from 40 to 150 m a.s.l., proved the existence of numerous local water bodies rather than one vast lake (Körnke 1930). Kondracki (1972) indicated that this area was under the influence of deglaciation, and consequently local shallow water bodies were formed in front of the ice sheet, in which glaciolimnic sediments were deposited at subsequently lower levels. In some sites, they also accumulated on dead ice, as evidenced by the occurrence of depressions of ice-dammed lakes. In the southern part of the Sępopol Lowland, sediments of ice-dammed lake origin, known as clay-loam sediments, prevail (Mańkowska, Słowiński 1979). These deposits are greasy, shiny, compacted and of dark brown colour. According to the geological map of Poland, glacial loam of dead ice origin occurs at the studied area (Giemza 2009).

The results of the analyses in the humus horizon revealed that the majority of soil samples were sandy clay loam (45% of samples) and fine sandy loam (35% of samples). The remaining 20% of samples were classified as loam, clay loam and clay (Soil Survey ..., 1999). The content of clay fraction ($ø < 0.002$ mm) varied and ranged from 15.0% to 31.0%, amounting to 21.7% on average (Table 1).

Most of the studied soil samples contained less than mean amounts of the clay fraction, which was indicated by the median value (21.0%) and confirmed the value of the coefficient of variation CV, which amounted to 21.0%. The calculated Moran index, however, suggested the absence of spatial correlation ($I = -0.050$) and the occurrence of a pure nugget effect, which was reflected by the semivariogram presented in Figure 1.

The content of water-extractable phosphate anions in the topsoil ranged between 5.55 and 22.05 mg kg^{-1} (13.09 mg kg^{-1} on average). The content of sulphate anions was higher, 23.5-38.2 mg kg^{-1} (29.18 mg kg^{-1} on average) and the content of nitrate anions was lower, 0.86-1.62 (1.04 mg kg^{-1} on average). The content of chloride anions oscillated between 16.6 and 24.9 mg kg^{-1} (Table 1). The coefficient of variation (CV) was low for all studied anions. The content of Cl^-, SO_4^{2-} and NO_3^- was lower than reported by Zissimos et al.

Table 1

Physical and chemical properties of studied soil samples

Parameter	Bulk density	Organic carbon	Clay fraction	PO_4^{-3}	SO_4^{-2}	NO_3^-	Cl^-
	($Mg\ m^{-3}$)	($g\ kg^{-1}$)	(%)	($mg\ kg^{-1}$)			
Min	1.315	12.3	15.0	5.55	23.50	0.86	16.60
Max	1.561	19.5	31.0	22.05	38.20	1.62	24.90
Mean	1.450	15.4	21.7	13.09	29.18	1.04	19.65
Geometric mean	1.450	15.4	21.3	12.42	28.96	1.02	19.50
Median	1.432	15.5	21.0	13.45	28.00	1.01	19.63
Standard deviation	0.08	1.6	4.6	4.06	3.75	0.21	2.54
CV (%)	5.5	10.3	21.0	15.70	13.39	0.04	6.15
Skewness	0.16	0.15	0.47	0.01	1.09	1.34	0.86
Kurtosis	-1.48	-1.79	-0.71	0.14	0.73	2.03	-0.08

CV – coefficient of variation

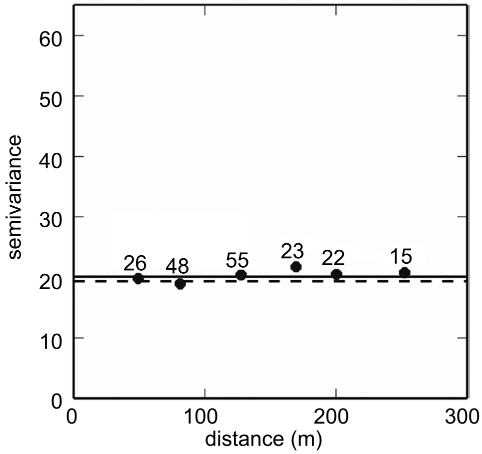

Fig. 1. Semivariogram of clay fraction: solid line – semivariogram model, dotted line – variance value, dots – number of pair of sampled values

(2014) in the soils of Cyprus. Lesser amounts of anions may be the result of leaching losses (Kuligod et al. 2008). The quantity of water soluble phosphate anions depends mostly on the exchange between the soil and soil solution (Shuai et al. 2014).

The studied soil contained low organic carbon amounts for arable soils, ranging from 12.3 to 19.5 g kg^{-1}, with an average of 15.4 g kg^{-1} (Table 1). The variability of OC content was low, which was confirmed by the low value of the coefficient of variation (10.3%). The content of OC within the field displayed a small but significant spatial autocorrelation (spatially varied), as indicated by the Moran index of 0.277 at *p*=0.001. Similarly, low values of the Moran index were found by Castellini et al. (2019) in soil samples collected from an experimental farm in southern Italy. The similarity is due to the fact that the studies were carried out at a relatively flat area of one field.

A positive value of the Moran index indicated that the studied adjacent areas had similar contents of OC. The square of the Moran index (I^2) suggested that the value of OC at 7.7% was defined by the values of variables at adjacent areas. The presence of spatial correlation between the sampling points has also been confirmed by the scope of the semivariogram's impact, which reached 44 m, and was higher than the distance between the sampling points. This type of a semivariogram has been described by the J-Bessel model and the model of nuggets. The value of the threshold variance (sill) amounted to 14.15 (g kg^{-1})^2 with the variance of nuggets amounting to 1.15 (g kg^{-1})^2 – Figure 2. These values indicate a small share of random variation in spatial distribution of OC in the soil cover of the studied field, which was also confirmed by a low value of the nugget effect (8.1%). Similar variations of these properties in the arable topsoil were obtained by Usowicz et al. (2004). The scope of spatial variability or similarity is related mainly to the size of the site.

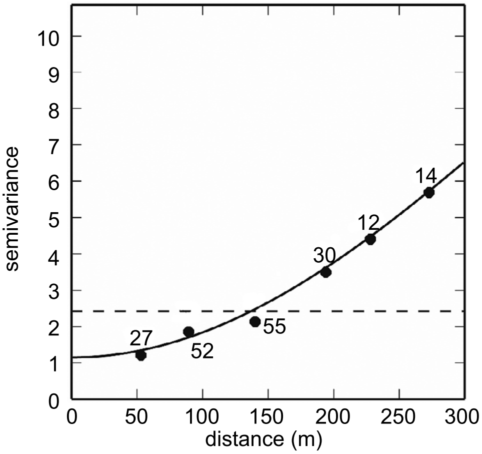

Fig. 2. Semivariogram of organic carbon: solid line – semivariogram model, dotted line – variance value, dots – number of pair of sampled values

Following Cambardella et al. (1994), the nugget-to-sill ratio can be a useful measure to describe the spatial structure of the studied variables. In particular, the nugget semivariance expressed as a percentage of the total semivariance enables comparison of the relative size of the nugget effect among studied variables, where the ratios < 25% indicate strong spatial dependence, the ratios between 25% and 75% indicate moderate spatial dependence, and the ratios > 75% indicate weak spatial dependence. The analysis of the nugget-to-sill ratios indicated an almost strong spatial dependence for organic carbon. The same results were found by Cambardella et al. (1994).

The degree of soil compaction in humus horizon of studied field varied which was confirmed by the values of bulk density ranging from 1.315 to 1.561 Mg m^{-3}, with an average of 1.450 Mg m^{-3} (Table 1). The bulk density in humus horizons of studied soils was higher than in arable horizons of typical and black vertisols formed from glaciolimnic sediments of Sępopol Lowland (Orzechowski et al. 2020). Most of the obtained results oscillated around the mean value, as evidenced by the median close to the mean value. A low variation of bulk density values was depicted by the low value of the coefficient of variation and the value of the geometric mean. The same values of arithmetic and geometric means proved the absence of outlier values of bulk density. However, the analysis of spatial autocorrelation (using the Moran index) showed the lack of it, as indicated by the low value of this index (-0.110), which was also confirmed by the course of the correlogram, in the area of I = 0 (Figure 3). Different results were obtained by Amirinejad et al. (2011), who found strong spatial correlation at a studied field. The values of total porosity also showed the lack of spatial correlation i.e. random distribution at the studied field. This was also confirmed by the Moran index, which amounted to -0.098 at p=0.663 (Table 2).

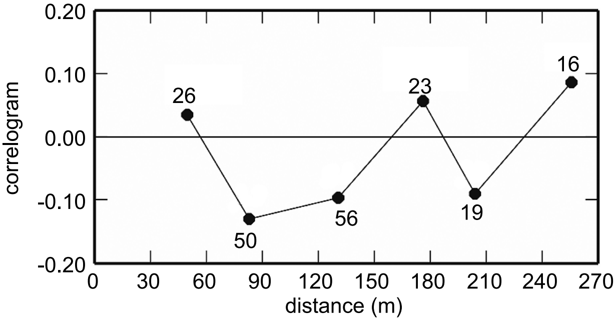

Fig. 3. Correlogram of bulk density: solid line – correlogram, dots – number of pair of sampled values

The total porosity of the humus horizon at the studied field was in the range of 39.1-48.5%, v/v, with an average of 44.1%, v/v, and did not show distinct variation (CV – 7.3% and low kurtosis – -1.42) – Table 3. The kurto-

Table 2

Moran's index of water properties

Parameter	Total porosity	Macropores	AWC	RAWC	SAWC	Micropores
	(%, v/v)					
Moran's index - I	-0.098	-0.234	-0.128	-0.244	0.102	-0.117
Z Score	-0.435	-1.766	-0.734	-1.969	1.504	-0.641
p-value	0.663	0.077	0.463	0.049	0.033	0.521

AWC – available water capacity, RAWC – readily available water capacity, SAWC – small pores available water capacity

Table 3

Statistical parameters of selected water properties

Parameter	Total porosity	Macropores	AWC	RAWC	SAWC	Micropores
	(%, v/v)					
Min	39.1	10.2	12.3	5.6	5.1	13.1
Max	48.5	15.9	20.3	13.6	9.9	17.6
Mean	44.2	13.0	15.5	8.5	7.0	15.8
Geometric mean	44.1	12.9	15.4	8.3	6.9	15.8
Median	45.3	12.9	15.5	8.1	6.9	16.1
Standard deviation	3.2	1.7	2.3	1.9	1.5	1.2
CV (%)	7.3	13.0	15.1	21.9	20.6	7.8
Skewness	-0.40	0.08	0.41	0.97	0.32	-0.83
Kurtosis	-1.42	-0.86	-0.64	1.59	-0.83	-0.02

CV – coefficient of variation, AWC – available water capacity, RAWC – readily available water capacity, SAWC – small pores available water capacity

sis lower than zero suggested flat (uniform) distribution and aggregation of the results around the mean value. The results also showed a small, left-sided asymmetry, which was confirmed by the negative value of skewness. Analysis of the volume of soil pores showed that the shares of the macro-, meso- and micropores in total porosity were similar. The mean shares amounted to: macropores – 13.0%, mesopores – 15.5%, v/v, micropores – 15.8%, v/v, with low variation, i.e. low CV values (Table 3).

The highest CV value was determined for mesopores (AWC 15.1%) and the lowest for micropores (7.8%), whose distribution showed a small, left-sided asymmetry. It was also confirmed by the value of the median, which was higher than the arithmetic mean (Table 3). In contrast, the distribution of the results for macropores was close to the symmetric one (Sk = 0.08), and the distribution of the results for mesopores showed a small, right-sided asymmetry (Sk = 0.41).

An analysis of spatial autocorrelation carried out using the Moran index (I) showed the lack of autocorrelation for mesopores and micropores. This was also confirmed by I value close to zero (-0.128 for mesopores and -0.117 for micropores) and high *p*-value amounting to 0.463 and 0.521, respectively, indicating the occurrence of random distribution (Table 2). The correlogram also confirmed the lack of autocorrelation (Figure 4). The spatial variability may be related to the varying texture, specifically the clay content, in the studied soils (see Table 1). Soil water retention depends largely on the soil texture, including the clay content (Castellini et al. 2019). Mesopores, and corresponding potential useful retention (AWC – available water content), can be divided into effective useful retention (RAWC – readily available water content) and retention of small capillaries (SAWC).

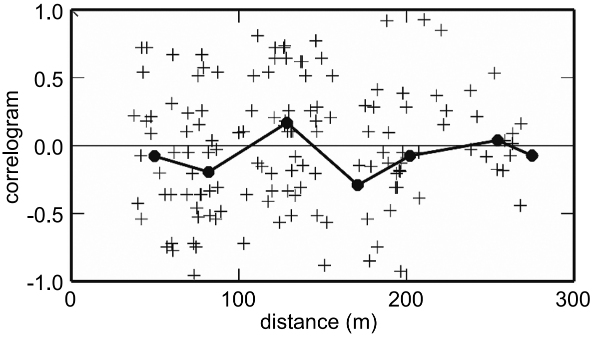

Fig. 4. Correlogram of macropores: solid line – correlogram, crosses – cloud of sample value

The RAWC in the studied humus horizon amounted to 5.6-13.6%, v/v, 8.5%, v/v on average, while SAWC was within the range of 5.1-9.9%, v/v (7.0%, v/v on average). Similar relations were also observed in Verisols of Sępopol Lowland (Orzechowski et al. 2020). Both soil water retention parameters had similar values of the coefficient of variation and the left-sided asymmetry, which was confirmed by the positive value of skewness and value of the median lower than the arithmetic mean (Table 3).

The analysis of spatial autocorrelation of RAWC indicated the presence of high and low values of RAWC located close to each other, which was also confirmed by the negative value of the Moran index. However, the course of the correlogram showed no spatial correlation because the value of the coefficient of correlation was close to zero (Figure 5). In contrast, spatial correlation for SAWC was determined, which was confirmed by the low value of the nugget effect (28.3%) and the range of the semivariogram of 177 m with a threshold variation of 2.38. This relationship was described by a spherical model (Figure 6). This analysis of the nugget-to-sill ratios indicated almost moderate spatial dependence for SAWC.

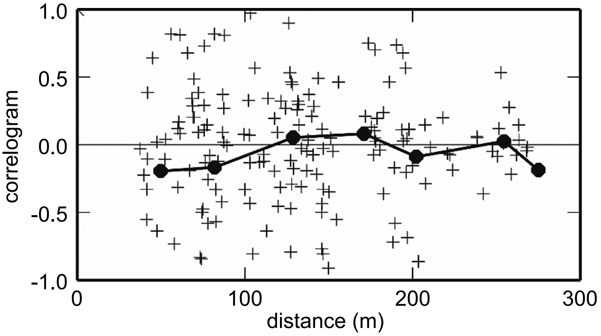

Fig. 5. Correlogram of readily available water capacity (RAWC): solid line – correlogram, crosses – cloud of sample value

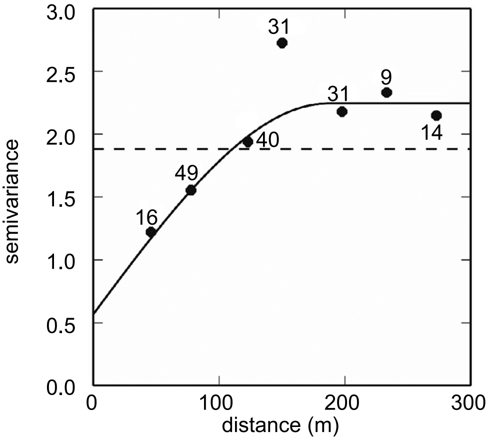

Fig. 6. Semivariogram of small pores available water capacity – SAWC (dots show the number of pair of sampled values)

CONCLUSIONS

At the set distance between sampling points on the studied field, spatial correlation occurred only for SAWC, which means that the distance between sampling sites was appropriate (correlation between the sites was reported). In relation to other properties, we suggest that it would be better to apply a reduction of the distance between sampling points or use of a lax grid (method of random points), which could result in varying the distance between sampling points. The study has both cognitive and practical meaning. The knowledge of spatial variability of soil properties on a field scale allows one to know the current conditions of arable soils and enables proper agricultural management.

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