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Research paper

Spatial variability of soil properties and cereal yield in a cultivated field on sandy soil

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ABSTRACT

Sandy soils are used in agriculture in different regions of the world. In Poland soils derived from sands occupy about 50% of agricultural area. Productivity of the soils depend on the soil properties that vary in the scale of field. This study aimed at determining and mapping the within-field variation of soil physical and chemical properties and grain yield of oats, rye, oats and triticale in 2001, 2002, 2003, 2015, respectively. The experiment was set up in a field (200 × 50 m) on sandy soil in Trzebieszów (region Podlasie, Poland). The soil measurements included sand, silt, clay, and organic carbon (SOC) contents, cation exchange capacity (CEC), pH in the topsoil (0–10 cm) and subsoil (30–40 cm) layers in 2001, and water content and bulk density in the topsoil layer in spring and summer 2002–2003. The yields of oats were assessed in 2001 and 2003 and those of rye and triticale in 2002 and 2015, respectively. The soil properties and cereal yields were determined at 33–55 points in a grid evenly covering the whole field area. The results were analyzed using classic statistics and geostatistics by constructing semivariograms and 2D mapping by Inverse Distance Weighting (IDW). The cereal grain yields were significantly positively correlated with the topsoil water content (SWC) (r = 0.295–0.711), clay content (r = 0.081–0.174), and SOC in the subsoil (r = 0.208–0.271) and CEC in both layers (r = 0.123–0.298) and negatively correlated with bulk density (BD) (r = –0.065 to −0.279). The spatial dependence determined by the "nugget-to-sill" ratio was moderate or weak for the silt and clay content, CEC, and pH (29–79%) and strong for SOC, BD, SWC, and crop yield (0.2–13.2%). The effective range of the spatial dependence for all studied quantities varied from 9.9 to 120 m. The cereal yields were positively and significantly correlated between all study years (r = 0.141–0.734), which indicates inter-annual similarity in their spatial distribution. The 2D maps based on the IDW allowed assessing how gradual or sharp the changes in the studied quantities from one place to another are. Similar spatial patterns of the SWC, SOC and CEC, and crop yields were observed. This is of importance in precise and sustainable field management aimed at increasing and aligning spatial crop productivity of the studied low-productivity sandy soils that will have to be used in crop production due to the current shortage of land resources and food supplies on a global scale.

1. Introduction

Sandy soils are used in agriculture in many regions of the world (Bronick and Lal, 2005; Schjønning et al., 2009; Jankowski et al., 2011). In Poland, approximately 50% of soils were derived from sands (Białousz et al., 2005; Rutkowska and Pikuła, 2013). Most of the soils show low content of soil organic matter ranging from 1 to 2% (Rutkowska and Pikuła, 2013) and exhibit low water holding capacity and high permeability. Consequently, in rain-fed environments with low and uneven precipitation, sandy soils induce water deficit during the growing season, which largely determines their relatively low productivity. Moreover, these soils have low cation exchange capacity associated with low both clay content and organic carbon content and hence low specific surface area (Usowicz et al., 2004). They are in general acidic (pH < 5.5) due to the post-glacial acidified parent material and leaching of exchangeable basic ions (Krasowicz et al., 2011; Behera and Shukla, 2015). On the other hand, they require relatively low energy inputs for tillage (Novák et al., 2014) and warm up quickly in the early spring to get the minimum soil temperature for plant growth. The largest area of sandy soils in Poland is used for cultivation of cereal crops.

Sandy soils are morphologically, chemically, and ecologically spatially variable at various scales (Jankowski et al., 2011; Pedrera-Parrilla et al., 2016). The main sources of the variability are related to soil-forming factors, topography (Jankowski et al., 2011; Silva and Alexandre, 2005), and management practices (Ozpinar and Cay, 2006;

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Ozpinar and Ozpinar, 2015; Gałka et al., 2016). Evaluating and understanding the spatial and temporal variability of the physical and chemical properties of soils and crop yields across a field are required for precise determining the best soil management practices and amendments to improve crop quantity and quality while being environmentally sustainable (Awe et al., 2015; Gajda et al., 2016; Aranyos et al., 2016). The within-field variability is an important source of uncertainty in crop production (Diacono et al., 2013). The use of geostatistical analysis facilitates identification of soil spatial variability in un-examined sites (Nielsen and Wendroth, 2003) and increases the accuracy of modeling soil behavior fluctuations (Serrano et al., 2010; Behera et al., 2011). Most studies dealing with spatial variability of soil properties in relation to crop yields were performed on more productive finely textured than coarsely textured soils although they are largely used in crop production.

The major objective of this study was therefore to determine the spatial variability of selected physical and chemical properties including the content of textural fractions, water, bulk density, organic carbon, cation exchange capacity, pH, and cereal grain yield in the field-scale on sandy soil in a four-year experiment. The specific objectives were to (i) identify soil properties that control cereal yields in different weather conditions during the growing season (ii) mapping soil properties and crop yields across the field using Inverse Distance Weighting.

2. Materials and method

2.1. Study area

The experimental field (200 × 50 m) is situated in Trzebieszów, region Podlasie, Poland (51°59'09.8"N 22°33'57.5"E) within a private farm. The region consists mostly of Podzol soils (WRB, 2015) derived from sandy and sandy loams of glacial origin, which are considered the least productive soils of Poland. More than 60% of the region area is used for crop production. A conventional tillage system after cereal harvest consists of stubble tillage (10 cm) using cultivator plus tooth harrows (1st half of August), moldboard ploughing (20–25 cm) and disking (10 cm) (2nd half of August) and tooth harrow (6 cm) to prepare seedbed for winter cereals (2nd half of September). As to spring crops moldboard ploughing (20–25 cm) is applied in late autumn and then in spring tillage operations similar as with winter cereals to prepare seedbed. Such tillage system is commonly used in the study area. Crop rotation includes mostly cereals and, intermittently, potatoes and legume species. The use of relatively light wheel tractors of about 2.5 to 3.5 Mg mass and combine harvesters of 7 to 10 Mg does not cause severe soil compaction. The stresses applied to the soil by the machinery range from about 30 to 80 kPa. The mineral fertilization was uniform on the whole field at an amount of 30–50 kg N ha^{-1}, 15–30 kg P ha^{-1}, and 20–30 K kg N ha^{-1}. The present management practices have been used for more than 30 years.

2.2. Weather

Fig. 1 illustrates the course of monthly mean air temperatures and rainfall sums for the years 2001, 2002, 2003, and 2015 in the study site. Average temperatures during the growing season (April-September) and annual temperatures in the successive years were 14.8, 15.8, 15.1, and 15.2 °C and 8.0, 8.7, 7.7, and 9.4 °C, respectively. The growing season temperatures in 2002, 2003, and 2015 proved to be among the highest during the past 50-year period for which the maximum was 16.3 °C. The respective sums of growing season and annual precipitations were 404, 285, 263, and 329 mm and 610, 550, 442, and 526 mm. The growing season precipitation rates in 2002, 2003, and 2015 were below the long-term average (567 mm).

2.3. Soil sampling and analysis

In 2001, we determined the textural composition with the sedimentation method of Bouyoucos's with modifications by Casagrande and Prószyński, (ISO, 1995), organic carbon content with the Tiurin titration method (Ostrowska et al., 1991), cation exchange capacity by neutralization of acidic groups with a barium chloride solution (ISO, 1995), and pH in 1 M KCl using a complex electrode Orion Research in the topsoil (0–10 cm) that was assumed to be representative for relatively uniform plough layer (0–25 cm) and subsoil layer (30–40 cm). Bulk density in cores of 100 cm^3 and a height of 5 cm was measured with the method developed by Blake and Hartge (1986) and the soil water content was assessed with a Time Domain Reflectometry meter (Malicki, 1990) in the topsoil layer in the spring and summer (just after harvest) in 2002 and 2003. The soil measurements were done at 50–55 points in a grid evenly covering the whole field area. Taking into consideration total area of the experimental field (1 ha) one measurement point corresponded to plot area of 182–200 m^2. The grain yields of physiologically similar cereals including oats (*Avena sativa*) (in 2001 and 2003), rye (*Secale cereale*) (in 2002), and triticale (*Triticosecale* Wittmack) (in 2015) were measured in 27–33 one-square-meter plots. In this case one measurement point corresponded to plot area of 303–370 m^2. Conducting of the experiment in the two stages (i.e. 2001–2003 and 2015) allowed assessing the effect of applying more frequent organic manure in the time span 2004–2015 on soil quality of the low productive soils. Completed in 2003 investigations were resumed in 2015 in the frame of the iSQAPER project (Horizon 2020) concerning assessment of soil quality in time and space. In this project our experimental field was accepted as a representative study site for sandy soils in continental climate. The cereals largely contribute in crop rotation of the region. Fig. 2 presents the spatial distribution of the measurement points of the soil properties and grain yields.

2.4. Geostatistical analysis

Basic statistical parameters i.e. the mean value, standard deviation, coefficient of variation (CV), and the maximum and minimum values for soil properties and crop yields were determined. The spatial dependence and variation of the quantities, $z(x_i)$ was studied with the help of semivariogram ($\gamma(h)$) that was calculated from the following equation:

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

where: $N(h)$ is the number of pairs of points distant from each other by h. The nugget values, sills, and ranges of spatial autocorrelation were determined, semivariogram models were fitted to the empirical values, and model fitting parameters were determined (Gamma Design Software, 2008):

$$\gamma(h) = C_0 + C[1 - \exp(h/A_0)]$$

where, $\gamma(h)$ semivariance for internal distance class h, h − lag interval, C_0–nugget variance ≥ 0, C − structural variance ≥ C_0, A_0–range parameter. In the case of the exponential model, the effective range for the major axis is equal 3A$_0$, which is the distance at which sill ($C_0 + C$) is within 5% of the asymptote. Proportion $C_0/(C_0 + C)$ is a measure of the proportion of sample variance ($C_0 + C$) that is explained by spatially structured variance C. This value will be 0 for a semivariogram with no nugget variance (where the curve passes through the origin); conversely, it will be 1.0 where there is no spatially dependent variation at the range specified. According to Chien et al. (1997), the spatial dependence ($C_0/(C_0 + C)$) < 25%, 25–75% and > 75% are strong, moderate, and weak, respectively.

To generate 2D maps of the studied quantities, the IDW (Gamma Design Software, 2008) was used:

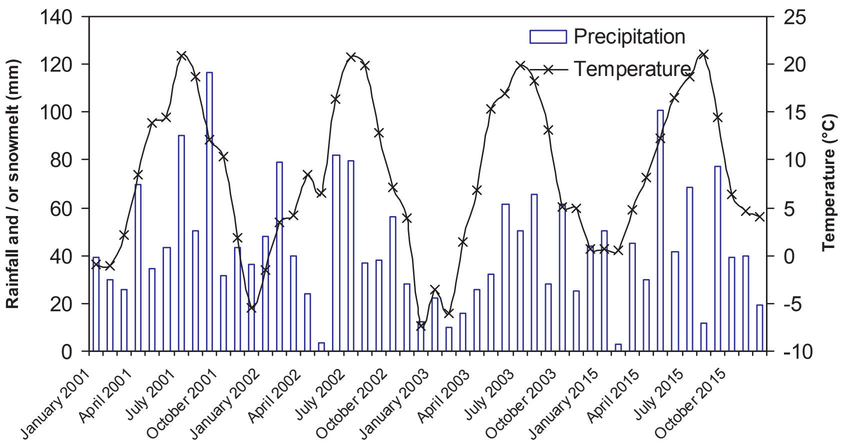

Fig. 1. Air temperature (average for months) and precipitation (month's sum) during the period of 2001–2003 and 2015.

$$z_j^*(h) = \sum \frac{z_i}{(h_{ij} + s)^p} \Big/ \sum \frac{1}{(h_{ij} + s)^p}$$

where $z_j^*(h)$ − estimated value for location j, z_i − measured sample value at point i, h_j − distance between $z_j^*(h)$and z_i, s − smoothing factor, and p − weighting power. At estimation of spatial distribution, the value of weighting power was mainly 3 and sometimes 2 and the smoothing factor was 1. The use of the IDW approach instead of kriging yielded better agreement with the measured data.

Fractal dimension (D) was estimated from the slope (H) of the log–log semivariogram plots from the formula (Burrough, 1983a, 1983b, 1983c; Perfect et al., 1990):

$$D = 2 - \frac{H}{2}$$

3. Results

3.1. Basic statistics

Basic statistical parameters of the soil properties for the topsoil (0–10 cm) and subsoil (30–40 cm) layers are listed in Table 1. The mean content of sand in the topsoil (89.2%) was slightly higher and that of silt (9.1%) slightly lower than in the subsoil, whereas the clay content and pH_{KCL} were almost the same in both layers (~1.6% and ~4.3, respectively). Mean SOC and CEC in the topsoil layer were 0.804% and 10.3 cmol kg^{-1} and by 61% and 24% lower in the subsoil layer. As indicated by the coefficient of variation, the largest variations were exhibited by the clay content (62.5–63.2%), intermediate − the silt content and CEC (34.0–49.7%), and the lowest − the sand content (4.8–4.9%) and pH (7.8–9.0%) in both the topsoil and subsoil layers. SOC was much more variable in the subsoil (80.2%) than topsoil layer (34.4%). According to classification proposed by Dahiya et al. (1984) CV values were low (0–15%) for the sand content and pH, high (> 75%) for the subsoil SOC and medium (15–75%) for the remaining variables.

The mean SWC (TDR) ranged from 0.027 to 0.298 m^3 m^{-3} (Table 2). Both in 2002 and in 2003, the SWC was greater in spring than in summer. The mean soil bulk density ranged from 1.206 to 1.409 Mg m^{-3} and increased from spring to summer in both years.

There was an inter-annual variation in the mean cereal grain yield, which ranged from 0.273 (in 2003) to 0.404 kg m^{-2} (in 2015) (Table 2). The range of variations was relatively greater in the maximum yield values (0.412–0.630 kg m^{-2}) than that in the minimum yields (0.177–0.200 kg m^{-2}). Both minimum and maximum values were the largest in 2015.

3.2. Relationships between yield and soil properties

Table 3 presents Pearson correlation coefficients (r) between the soil parameters studied and cereal grain yield at $p < 0.05$. They were related to the study year. In 2001 and 2015, the yield was significantly and negatively correlated with the topsoil sand content (–0.274 and −0.298) and positively correlated with the silt content (0.249 and 0.294), while in 2002 and 2003 it was positively correlated with the subsoil sand content (0.222 and 0.056) and negatively correlated with the subsoil silt content (–0.089 and to −0.246). In 2015, however, the crop yield was significantly and negatively correlated with the subsoil sand content (–0.137) and positively correlated with the silt content (0.127). Topsoil SOC correlated with the yield positively in 2001 and 2015 (0.119 and 0.221) and negatively in 2002 (–0.154). Irrespective of study year, the cereal grain yield was positively correlated with the topsoil clay content (0.081–0.174), SOC in the subsoil layer (0.208–0.271), and CEC in both layers (0.123–0.298).

Among more variable soil properties measured in 2002 and 2003, the topsoil SWC was mostly positively correlated with cereal yields. The correlations between the soil water content in spring and summer and the crop yield were stronger in 2002 (0.711 and 0.660) than in 2003 (0.295 and 0.519). A significant negative relationship was observed between the crop yield and topsoil bulk density (from −0.065 to −0.279) with weaker correlations in summer than spring. It is worth

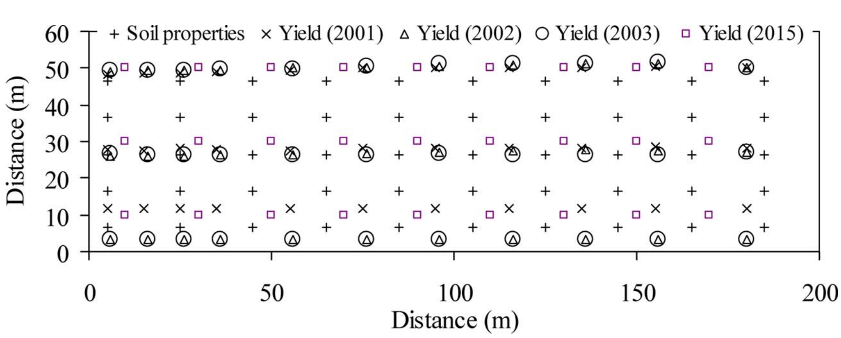

Fig. 2. Distribution of measurement points for soil properties and grain yield in the sandy soil field (yield point equals one m^2).

Table 1
Summary statistics for content of soil textural fractions, pH $_{KCl}$, soil organic carbon content (SOC) and cation exchange capacity (CEC) in sandy soil field.

Parameter	% content of fractions			pH $_{KCl}$	SOC	CEC
	2–0.02 (mm)	0.02–0.002 (mm)	< 0.002 (mm)	(–)	(%)	(cmol kg^{-1})
Layer 0–10 cm						
Number of points	50	50	50	50	50	50
Mean	89.2	9.1	1.6	4.18	0.804	10.3
Standard deviation	4.79	4.54	1.03	0.378	0.276	3.82
Coefficient of variation	5.4	49.7	62.5	9.0	34.4	37
Minimum	74	2	0	3.75	0.1	4.53
Maximum	96	23	5	5.69	1.675	23.2
Layer 30–40 cm						
Number of points	50	50	50	50	50	50
Mean	86.9	11.6	1.5	4.3	0.313	7.8
Standard deviation	4.26	3.95	0.97	0.337	0.251	3.1
Coefficient of variation	4.9	34.0	63.2	7.8	80.2	39.4
Minimum	76	2	0	3.81	0.005	2.2
Maximum	97	21	5	5.77	0.945	13.8

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Table 2
Summary statistics for the water content (TDR) and bulk density of the sandy soil and cereal grain yield.

	Water content (m^3 m^{-3})			
Parameter	20.04.2002	31.07.2002	16.05.2003	5.08.2003
Number of values	55	55	55	50
Mean	0.148	0.149	0.122	0.087
Standard deviation	0.047	0.052	0.034	0.031
Coefficient of variation	31.7	34.6	27.7	35.7
Minimum	0.082	0.064	0.058	0.027
Maximum	0.298	0.321	0.204	0.175
	Bulk density (Mg m^{-3})			
Number of values	50	50	55	50
Mean	1.386	1.409	1.206	1.304
Standard deviation	0.112	0.097	0.123	0.093
Coefficient of variation	8.1	6.9	10.2	7.1
Minimum	1.051	1.159	0.957	1.097
Maximum	1.574	1.689	1.566	1.499
	Grain yield (kg m^{-2})			
	Oats (2001)	Rye (2002)	Oats (2003)	Triticale (2015)
Number of values	33	33	33	27
Mean	0.356	0.302	0.273	0.404
Standard deviation	0.101	0.069	0.057	0.123
Coefficient of variation	28.3	22.8	20.7	30.4
Minimum	0.181	0.177	0.180	0.200
Maximum	0.617	0.556	0.412	0.630

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noting that the cereal yields were positively correlated between all study years (from 0.141 to 0.734), which indicates inter-annual similarity in their spatial distribution

3.3. Geostatistical analysis

The distributions of the measurement data were similar to the normal distribution and thus met the condition of a stationary or quasi-stationary process in geostatistical analysis with the exception of the sand and silt contents in the subsoil layer, where it was obtained after log-natural transformation. The exponential models fairly well matched the empirical semivariogram data for all quantities (Table 4).

The spatial dependencies ("nugget-to-sill") for the silt and clay contents and CEC and pH were moderate and weak (29–79%) and strong for SOC, BD, SWC, and crop yield (0.2–13.2%). The nugget effect occurred mostly in the sand, silt, and clay contents (0.83–14.6) and CEC (2.99–10.8) with lower values in the subsoil than topsoil layer. As to the other soil properties and crop yields, the nuggets values ranged from 0.00001 to 0.054. The sills were the greatest for the content of the textural fractions (0.946–22.5) and CEC (10.1–14.42) with lower values in the subsoil than topsoil. In turn, for all the other soil properties and crop yields, they were much lower and ranged from 0.000045 to 0.12. The sill values of the topsoil SWC and bulk density were similar in spring and summer both in 2002 and in 2003 and varied from 0.0011 to 0.014.

The effective range of the spatial dependence for all studied quantities varied from 9.9 for the clay content in the topsoil layer to 120 m for the water content in spring 2002. The ranges for soil textural fractions, SOC, and pH were greater in the subsoil than topsoil but the reverse was true in the case of CEC. For the soil water content and bulk density, the ranges were generally lower in spring than in summer. The range for the crop yields varied from 26.7 to 45.9 m.

Evaluation of the spatial distribution of the studied quantities using the fractal theory showed that the contents of sand, silt, and clay, SOC, CEC had the highest fractal dimension values (1.95–2.0) and hence were highly randomly distributed. In all cases, the values were slightly greater (by 0.01–0.04) in the topsoil than subsoil layer. Lower fractal dimensions were recorded for SWC, bulk density, and crop yields (1.8–1.95).

3.4. Spatial distributions of soil characteristics and crop yield

Spatial distribution of SOC, CEC, and SWC that mostly correlated with the crop yield and the crop yields themselves are presented in the IDW maps (Figs. 3–5). Analysis of the maps indicates that the spatial distribution of SOC and CEC was more diverse in the topsoil than subsoil layer with generally lower values of both variables in the latter. There is a general similarity in the distributions of the inherent sand, silt, and clay contents between the topsoil and subsoil layers. The main part of the study field was covered by acid soils with $pH_{KCl} < 4.8$ (Fig. 3) at relatively low CV (7–9%) (Table 1). Comparison of the maps indicates that the increased SWC during both spring and summer on the right side of the studied field (Fig. 4) corresponds with the increased yield of oats, rye, and triticale (Fig. 5). This part of the studied field also exhibited greater CEC in the topsoil and greater SOC in the subsoil, especially in the gently sloping area in the upper right corner of the field (Fig. 3). However, in the relatively flat area in the lower middle and left parts of the field, the relatively low yields are accompanied by relatively low contents of silt, clay, SOC, CEC, and SWC.

Table 3
Correlation coefficients (r) between soil variables and cereal grain yield.

	Variables	2001 Oats (kg m^{-2})	2002 Rye (kg m^{-2})	2003 Oats (kgm^{-2})	2015 Triticale (kgm^{-2})
Layer 0–10 cm	2–0.02 (mm)	**−0.274***	−0.020	−0.022	**−0.298**
	0.02–0.002 (mm)	**0.249**	−0.013	0.005	**0.294**
	< 0.002 (mm)	**0.174**	**0.147**	**0.081**	**0.089**
	SOC (%)	**0.119**	**−0.154**	−0.010	**0.221**
	CEC (cmol kg^{-1})	**0.174**	**0.123**	**0.152**	**0.193**
Layer 30–40 cm	2–0.02 (mm)	0.010	**0.222**	**0.056**	**−0.137**
	0.02–0.002 (mm)	−0.015	**−0.246**	**−0.089**	**0.127**
	< 0.002 (mm)	0.018	0.036	**0.120**	**0.085**
	SOC (%)	**0.271**	**0.267**	**0.244**	**0.208**
	CEC (cmol kg^{-1})	**0.193**	**0.123**	**0.173**	**0.298**
Layer 0–10 cm					
Spring	Water content TDR (m^3 m^{-3})		**0.711**	**0.295**	
	Bulk density (Mg m^{-3})		**−0.169**	**−0.235**	
Summer	Water content TDR (m^3 m^{-3})		**0.660**	**0.519**	
	Bulk density (Mg m^{-3})		**−0.065**	**−0.279**	
Year					
2001	Oats yield (kg m^{-2})	1	**0.348**	**0.398**	**0.705**
2002	Rye yield (kg m^{-2})		1	**0.734**	**0.141**
2003	Oats yield (kg m^{-2})			1	**0.148**
2015	Triticale yield (kg m^{-2})				1

SOC, soil organic carbon; CEC, cation exchange capacity.
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*Correlation coefficients in bold are significant at the $p < 0.05$).

4. Discussion

This study provides information on how cereal grain yields are correlated and spatially dependent on selected soil physical and chemical properties. The discussion focuses on the spatial patterns of the soil properties and cereal yield in the context of sustainable field management to raise and line up the yields on the sandy soil.

4.1. Correlation analysis

In general, the Pearson correlation coefficients between the studied soil properties and crop yields are rather low (Table 3). This is related to the fact that crop yields under field conditions are a resultant of both positive and negative effects of soil factors, weather conditions, and different spatial distribution patterns of soil properties and crop yields. The highest positive and significant correlations in our study were obtained for SWC, which were from 0.519 and to 0.711 at three of four occasions. This indicates that management to increase water storage and use by crops in sandy soils is particularly critical for increasing crop productivity.

It is worth noting that the cereal yields were correlated significantly and negatively with soil bulk density varying from 0.957 to 1.574 Mg

Table 4
Semivariogram parameters of soil properties and crop yields.

	Variables	Model	C_0 (volume)^2	$C_0 + C$ (volume)^2	$C_0/(C_0 + C)$	*A (m)*
Layer 0–10 cm	2–0.02 (mm)	Exponential	9.1	22.5	0.404	15.3
	0.02–0.002 (mm)	Exponential	14.6	20.4	0.716	12.9
	< 0.002 (mm)	Exponential	0.83	1.05	0.790	9.9
	pH ($_{KCl}$)	Exponential	0.054	0.095	0.568	39.6
	SOC (%)	Exponential	0.0105	0.0795	0.132	11.1
	CEC (cmol kg^{-1})	Exponential	10.84	14.42	0.752	19.8
Layer 30–40 cm	2–0.02 (mm)	Exponential	1.49	17.75	0.084	21.3
	0.02–0.002 (mm)	Exponential	1.51	15.38	0.098	19.8
	< 0.002 (mm)	Exponential	0.068	0.946	0.072	12
	pH ($_{KCl}$)	Exponential	0.046	0.120	0.383	66
	SOC (%)	Exponential	0.0038	0.0586	0.065	11.4
	CEC (cmol kg^{-1})	Exponential	2.929	10.1	0.290	18.9
Date 2002	Layer 0–10 cm					
Spring	Water content TDR (m^3 m^{-3})	Exponential	0.000337	0.00120	0.281	120
	Bulk density (Mg m^{-3})	Exponential	0.00154	0.01258	0.122	36
Summer	Water content TDR (m^3 m^{-3})	Exponential	0.000045	0.00158	0.028	21
	Bulk density (Mg m^{-3})	Exponential	0.00549	0.00975	0.563	99
Date 2003	Layer 0–10 cm					
Spring	Water content TDR (m^3 m^{-3})	Exponential	0.000106	0.001102	0.096	24.3
	Bulk density (Mg m^{-3})	Exponential	0.00145	0.0143	0.101	12
Summer	Water content TDR (m^3 m^{-3})	Exponential	0.000438	0.000936	0.468	105
	Bulk density (Mg m^{-3})	Exponential	0.00008	0.0076	0.011	24.9
Date						
2001	Oats yield (kg m^{-2})	Exponential	0.00119	0.01058	0.112	26.7
2002	Rye yield (kg m^{-2})	Exponential	0.00001	0.00593	0.002	45.9
2003	Oats yield (kg m^{-2})	Exponential	0.00028	0.00395	0.071	30.3
2015	Triticale yield (kg m^{-2})	Exponential	0.00178	0.015760	0.113	43.2

C_0 is the nugget variance, $C_0 + C$ is the sill, A − *effective range.*

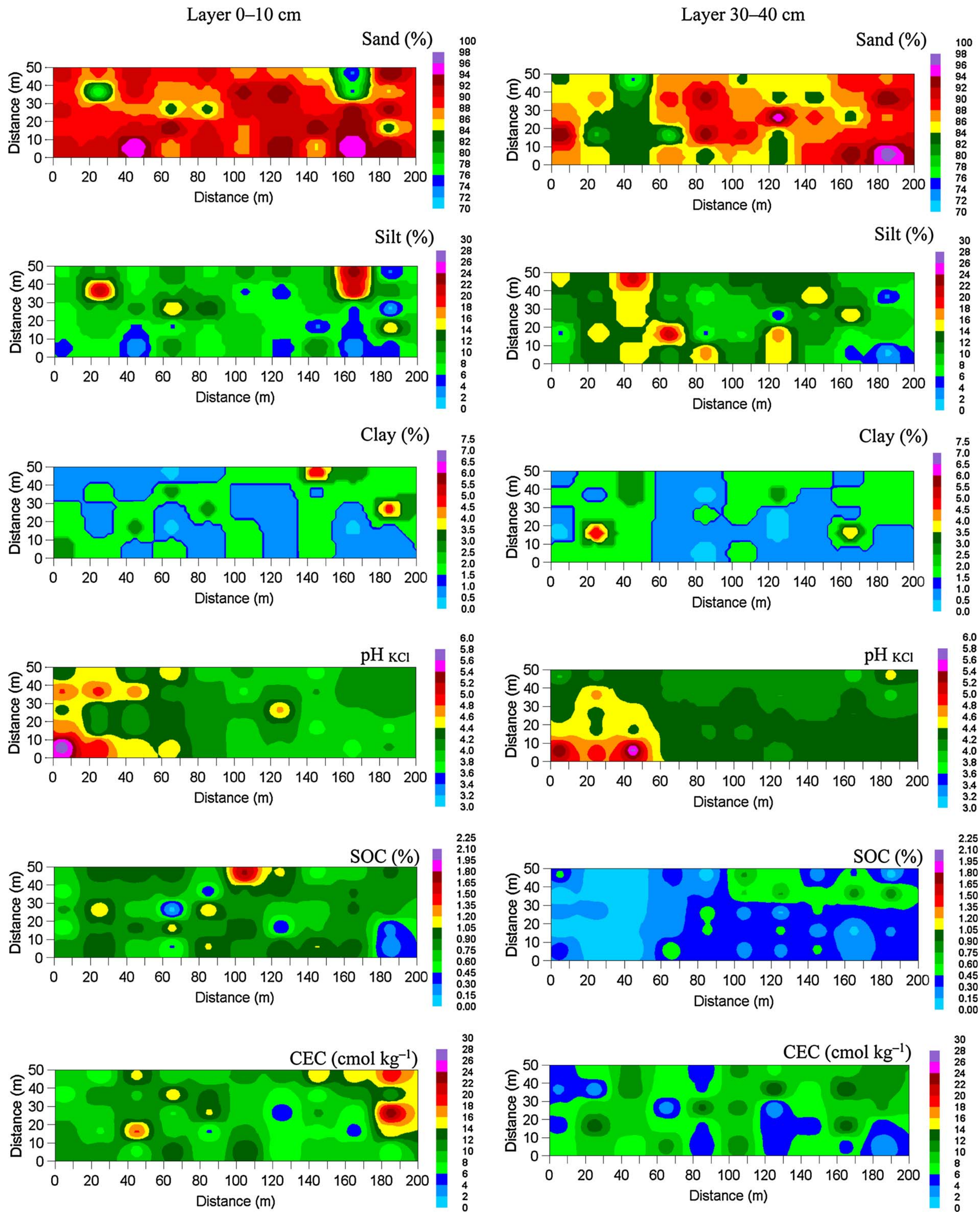

Fig. 3. Spatial distribution of the sand, silt, and clay content, pH_{KCl}, soil organic carbon (SOC) and cation exchange capacity (CEC) for the 0–10 cm and 30–40 cm layers in the sandy soil field.

m^{-3}, corresponding to the degree of compactness (ratio of the actual to maximum bulk density) from 53 to 88%. Research has shown that this range of the degree of compactness does not cause a significant decrease in the crop yield due to insufficient aeration (air-filled porosity $< 0.10\ m^3\ m^{-3}$) or excessive strength (penetration resistance > 2 MPa) (Håkansson and Lipiec, 2000; Ozpinar and Cay, 2006; Reichert et al., 2009b; Suzuki et al., 2013). Visual observations of the field carried out by the farmer indicate no excessively wet periods that could induce insufficient aeration (oxygen stress) occur on the highly permeable soil. Hence, the negative relationship between the cereal yield and soil bulk density in our study can result mostly from excessive penetration resistance in denser soil. Studies conducted under more controlled conditions by Whalley et al. (2006, 2008) suggest that any increase in soil strength due to drying or compaction reduces root growth and wheat productivity. Similar results were found in field studies under Mediterranean conditions (Ozpinar, 2010; Ozpinar and

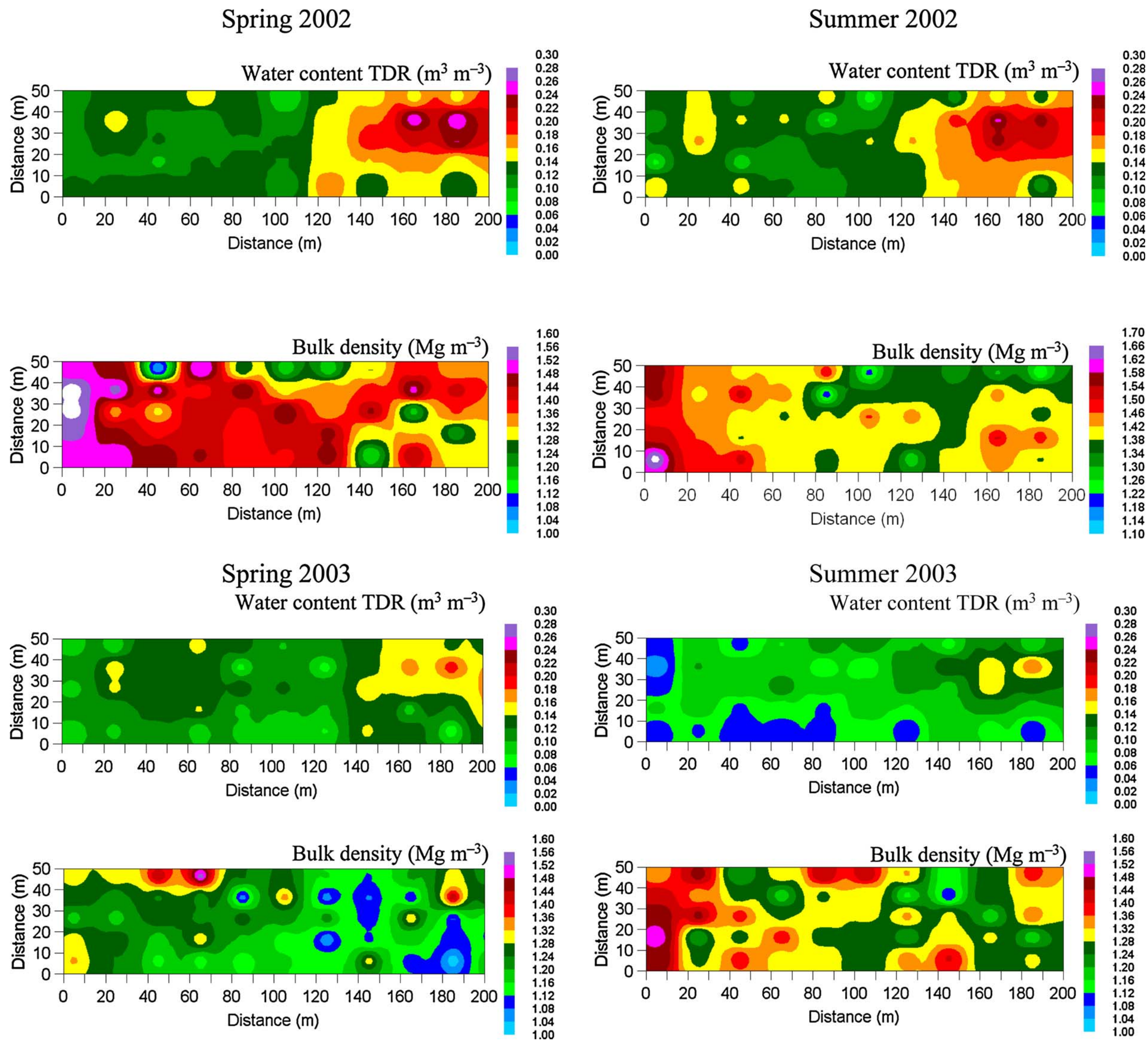

Fig. 4. Spatial distribution of the water content (TDR) and bulk density in the cultivated field for spring and summer measurements.

Ozpinar, 2015). In a sandy environment, root growth can be also restricted by hindered displacement of sand particles due to interlocking despite low penetrometer resistance (Lipiec et al., 2016).

The positive and significant correlations in the cereal grain yields between all four respective study years based on grading of each measurement point indicate similar spatial distribution of the crop yield each year (Table 3). The highest correlations were noted between 2002 and 2003 (0.734) and between 2001 and 2015 (0.705); they are indicative of inter-annual yield pattern persistence. The former might be enhanced by a similar and small amount of rainfall especially during the critical period of intensive growth (May) at a relatively high temperature during both growing seasons and by application of manure in 2002. However, the latter may have resulted from the fairly high and comparable total amount and favorable distribution of rainfalls during 2001 and 2015 growing seasons. The values of the year-to-year correlations are similar to those obtained for wheat grown in larger fields (75–125 ha) under drier and warmer conditions of South Australia (Florin et al., 2009).

4.2. Geostatistical analysis

The geostatistical analysis showed that the ranges for the contents of inherent textural fractions and slightly variable SOC and CEC were shorter (9.9–19.8 m depending on depth) than for the more variable SWC and bulk density (12–120 m). The short-range variation of the former can be further supported by the greater nugget/sill ratios (Cambardella et al., 1994) and the higher fractal dimensions (see Section 3.4). The short-range variation for soil textural fractions can be related with the glacial origin of the sandy soils and associated washing and sorting by melting and transportation (Woronko and Pochocka-Szwarc, 2013). However, the longer-range variation of SWC and bulk density can be in part a result of uneven growth of plants themselves due to inherent soil spatial variability and management practices (Sadeghi et al., 2006; Fu et al., 2010). This explanation can be supported by the longer ranges of the SWC and bulk density in summer than in spring. Overall, the results imply that the sampling interval for representative results should be smaller for CEC than SWC and bulk density and much smaller for SOC and textural fractions.

4.3. 2D maps

By analyzing the distributions of soil properties in a given field along with knowledge of the impact of given property on plant growth, one can identify places with the highest, moderate, and low crop yield. Comparison of within-field maps of the SWC, SOC, and CEC with that of the crop yield allows identification of consistently homogeneous sub-

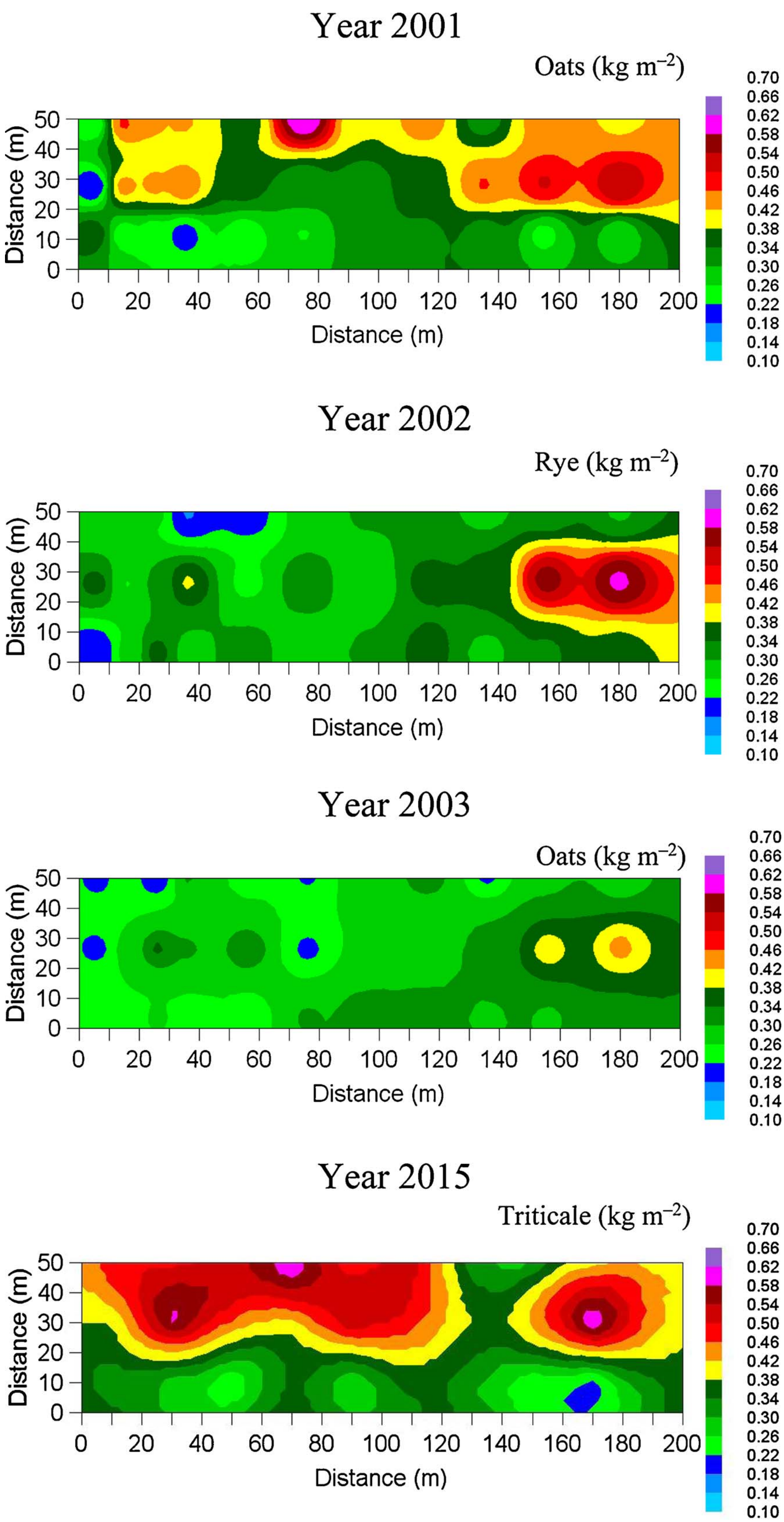

Fig. 5. Spatial distribution of the cereal grain yield.

field areas for further management (management zones) (Stafford, 2006; Moral et al., 2010). This implies that the three soil properties along with initial assessment of soil texture can be a minimum set used to determine changes in productivity and quality of sandy soils. The areas with the lowest yield occur in the drier upper and flat part and those with the highest yield in the wetter part along with the higher SOC and CEC at the bottom of the slope in the upper right corner of the field (Figs. 3–5). This distinction may justify increased fertilization and seeding rates in wetter areas to improve further their productivity. In general, farmers apply uniform rates of fertilizers without taking into account the spatial variability of plant available SWC and SOC, and CEC, which affect water and nutrient uptake. This can result in over- or under-fertilization and decreasing efficiency of the fertilizer use and affect crop growth and environmental pollution (Usowicz et al., 2004; Basso et al., 2013), particularly in dry areas. The pollution risk refers especially to nitrogen fertilizers with a large agricultural input in cereal production (Diacono et al., 2013) and proneness to losses due to ammonia volatilization, denitrification, runoff, and leaching (Montemurro, 2009; Lipiec et al., 2011).

It is worth noting that the magnitude of spatial variations in the cereal yield was lower in 2015 than in 2001–2003. This was clearly indicated by the relatively large areas of similar and greater yields in 2015, especially in the upper part of the field (Fig. 5). The larger spatial alignment of the crop yield in 2015 can result in part from the application of increased quantity of solid manure by the farmer in the time span 2004–2015 based on the results from the first stage of this study in 2001–2003, which indicated low SOC on the experimental field. This practice resulted in an increased SOC on average by 6%. The increase in soil productivity in 2015 relative to years 2001–2003 could also be explained by the greater rainfall in May (Fig. 1), i.e. a period when cereals in Poland grow intensively and use most water (Radzka et al., 2008). The above analysis highlights the potential for soil improving practices to make sandy soils more productive and provides better insight into the interactions between the soil, climate, and crop productivity.

4.4. Further studies

There are ongoing investigations within EU program Horizon 2020 based on the so-far collected spatial data for better matching the appropriate soil-improving cropping systems with the spatial variability of crop yield on sandy soils. The recently available new developments for non-invasive soil measurements, i.e. GPS-equipped yield monitors and variable-rate technology (Diacono et al., 2013), will be helpful in precise and sustainable field management to increase and align spatial productivity and hence improve the relatively low overall crop yield ratio (actual over potential) of sandy soils (Królczyk et al., 2014). The application of a novel multivariate geostatistical approach, factorial cokriging analysis, and the first regionalized factors (with eigenvalues greater than one) (Diacono et al., 2013) may help to delineate management zones with a size manageable by a farmer when the yields are not spatially fixed to the same places from one growing season to the next. The need for better exploration of low-productivity sandy soils results from the current shortage of land resources and food world-wide (Reichert et al., 2009a; Lal, 2011). Therefore, such soils will have to be improved and used in agriculture and agroforestry systems worldwide (; Królczyk et al., 2014). Sandy soils are particularly suitable for such crops as rye and potatoes (Vink and van Zuilen, 1974) as well as peanuts (Zhao et al., 2015).

5. Conclusions

1. The cereal grain yields were correlated significantly and positively with the topsoil and subsoil cation exchange capacity, topsoil water content and clay content, and subsoil organic carbon content, and negatively correlated with topsoil bulk density.
2. The exponential models fairly well matched the semivariogram empirical data and in general showed strong and moderate spatial dependency for all soil properties and crop yields. Their effective range varied from 9.9 to 120 m.
3. 2D maps allowed identification of rather homogeneous sub-field areas with the soil water content, organic carbon content, cation exchange capacity, pH_{KCl}, and cereal grain yield. These soil properties along with soil texture should be included in the minimum data set to assess the quality of sandy soils. At the same time, the maps provide opportunity to improve crop productivity on sub-field areas with low soil quality.
4. Overall, the results showed that geostatistical analysis is an useful tool to determine spatial interrelationships of crop yield and soil properties in the scale of agricultural field.

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