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Spatial relationships among cereal yields and selected soil physical and chemical properties

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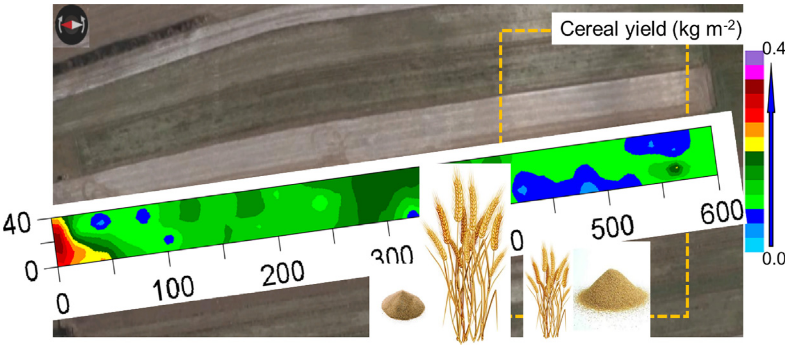
HIGHLIGHTS

- Geostatistical analysis allowed delineating homogeneous low productive field area.
- The low productive field area contains more sand and less silt and water in soil.
- Spatial distribution of cereal yield and soil CEC, SOC and pH were related.
- Kriging and remote sensing maps can help in upscaling management practices.

GRAPHICAL ABSTRACT



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ABSTRACT

Sandy soils occupy large area in Poland (about 50%) and in the world. This study aimed at determining spatial relationships of cereal yields and the selected soil physical and chemical properties in three study years (2001–2003) on low productive sandy Podzol soil (Podlasie, Poland). The yields and soil properties in plough and subsoil layers were determined at 72–150 points. The test crops were: wheat, wheat and barley mixture and oats. To explore the spatial relationship between cereal yields and each soil property spatial statistics was used. The best fitting models were adjusted to empirical semivariance and cross-semivariance, which were used to draw maps using kriging. Majority of the soil properties and crop yields exhibited low and medium variability (coefficient of variation 5–70%). The effective ranges of the spatial dependence (the distance at which data are autocorrelated) for yields and all soil properties were 24.3–58.5 m and 10.5–373 m, respectively. Nugget to sill ratios showed that crop yields and soil properties were strongly spatially dependent except bulk density. Majority of the pairs in cross-semivariograms exhibited strong spatial interdependence. The ranges of the spatial dependence varied in plough layer between 54.6 m for yield × pH up to 2433 m for yield × silt content. Corresponding ranges in subsoil were 24.8 m for crop yield × clay content in 2003 and 1404 m for yield × bulk density. Kriging maps allowed separating sub-field area with the lowest yield and soil cation exchange capacity, organic carbon content and pH. This area had lighter color on the aerial photograph due to high content of the sand and low content of soil organic carbon. The results will help farmers at identifying sub-field areas for applying localized management practices to improve these soil properties and further spatial studies in larger scale.

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1. Introduction

Soil physical and chemical properties and crop yields vary spatially and temporally on different scales. The variability is largely influenced by pedogenesis processes (Gilliam and Dick, 2010; Moradi et al., 2016), topography (Jankowski et al., 2011), and agricultural practices including tillage operations, compaction, chemical application, and harvesting (Alaoui et al., 2011; Gajda et al., 2016; Ozpinar and Ozpinar, 2015; Schjønning et al., 2009).

Knowledge about soil variability is essential in precise determination of the most appropriate and localized management practices and amendments to improve and align soil conditions and quality for an effective use of water and nutrients and crop growth (Bölenius et al., 2017; Kumhálová and Matějková, 2017; Usowicz and Lipiec, 2017). For example, variable-rate management practices such as fertilization and irrigation based on spatial data of chemical and soil water status (Sadler et al., 2005; Pedrera-Parrilla et al., 2016; Mubarak et al., 2016) help to limit the use of agricultural chemical and water and to reduce leaching and environmental pollution (Adamchuk and Viscarra Rossel, 2011; Bogunovic et al., 2014; Hedley and Yule, 2009). Further, analysis of the spatial dependency of soil water status along with weather conditions are key issues for modelling soil water dynamics and balance (Awe et al., 2015; Kędzior and Zawadzki, 2016; Schwen et al., 2014).

The spatial distribution of different soil properties can be evaluated by classical and spatial statistics using direct semivariograms and cross-semivariograms (Goovaerts, 1999; Webster, 2008). Semivariograms describe the dependence of the values of a given variable on the distance between the sampling sites and thereby the spatial structure of the variation. Thus, they help in designing a sampling setup including the number of samples required for adequate description of the soil and yield in agricultural areas (Jabro et al., 2010; Moradi et al., 2016). When different variables are related, their joint spatial patterns can be evaluated by cross-semivariograms. Cross-semivariogram data and maps obtained with the co-kriging procedure allow prediction of time-consuming and/or costly variables from those measured more easily. Using cross-semivariograms, Jabro et al. (2010) found that soil penetration resistance was spatially correlated with water content, total porosity, and saturated hydraulic conductivity. The study by Walter et al. (2002) showed spatial interdependence between weed species density and soil properties such as clay, phosphorus contents and pH, and the extent of the spatial dependence varied among the study years. However, little information is available about the spatial and inter-annual variability of crop yields and soil properties, especially on a field scale, although it is the main methodological means for implementing precision agriculture technology of different intensity to compensate and improve soil conditions for strengthening crop growth (Diacono et al., 2013; Usowicz et al., 2009; Webster, 2008).

Therefore, the objectives of the three-year study were to determine the field-scale spatial variability of cereal yields and selected inherent soil properties, including textural fractions, and slightly variable properties such as pH, soil organic carbon (SOC), cation exchange capacity (CEC), and dynamic soil water content and bulk density. Classical statistics and spatial statistics including descriptive statistics, direct semivariograms, cross-semivariograms and kriging maps were used to explore the spatial variability of variables and the spatial relationships between the cereal yields and the soil properties. This study will support research aiming at development of soil improving cropping systems within the SoilCare project (EU Horizon 2020 Program) realized in 2016–2021.

2. Materials and methods

2.1. Study area and tested cereals

The experiment was conducted during the cropping seasons in 2001, 2002 and 2003 in Łuków County, Podlasie region, Poland (51°58′51.8″N 22°32′22.9″E) on a field (600 × 40 m) within a private farm. The tested crops in the successive years were wheat (*Triticum aestivum* L.), a wheat-barley (*Hordeum vulgare* L.) mixture and oats (*Avena sativa* L.). The planting and harvest of all crops were done in the first decade of April and first decade of August each year. The experimental field was localized in a low productive area composed mainly of Podzol soils (IUSS Working Group WRB, 2015) derived from glacial sandy material. Ploughing tillage system and crop rotation including wheat, oats, barley, rye, triticale, maize and infrequently potatoes are commonly used in the region.

The mean temperatures in the growing season (April–September) and annual temperatures in 2001, 2002, and 2003 were 14.8, 15.8, and 15.1 °C and 8.0, 8.7, and 7.7, °C, respectively. Corresponding the growing-season and annual precipitations were 404, 285, and 263 mm and 610, 550, and 442 mm. Both the growing-season and annual precipitations in 2002 and 2003 were lower than the long-term averages (351 and 567 mm). It should be noted that the monthly average air temperature in the period of intensive cereal growth (May–July) was the highest in 2003 along with a suitable distribution of rainfall amounts during growing season (Fig. 1).

2.2. Soil and cereal yield analyses

Fig. 2 displays the spatial distribution of the measurement points of the soil properties and grain yields. The soil measurements including textural fractions, pH, SOC, CEC and water content were performed in 150 points evenly covering the whole field area (40 × 600 m). However, bulk density was determined in less number of points (116 at spring 2002 and 130 in autumn 2002 and in both seasons in 2003) that were located at the same selected points as with other soil properties. The grain yields of all cereals were measured in 72 one-square-meter plots located close to the measurement points of the soil properties.

In 2001, we determined the soil textural composition with the sedimentation method of Bouyoucos's with modifications by Casagrande and Prószyński, (ISO, 1995), SOC with the Tiurin titration method (Ostrowska et al., 1991), CEC 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 plough layer (0–25 cm) and subsoil layers (25–40 cm). BD was measured with the method developed by Blake and Hartge (1986) using 100 cm^3 cores with a height of 5 cm, and the soil water content was determined with a Time Domain Reflectometry meter (Malicki, 1990) in the plough layer in the spring and summer (just after harvest) in 2002 and 2003.

2.3. Data analysis

2.3.1. Classical statistics

Basic statistics including the mean, standard deviation, minimum, maximum, kurtosis, and skewness for each soil property and cereal yields were calculated. The values of both kurtosis and skewness equal 0 indicate in general symmetrical distribution with similar the right tail (positive) and left tail (negative) of the distribution curve. If one tail is longer than the other, then there is asymmetric distribution. Based on the coefficient variation (CV) values the variability of soil properties and yields was classified as low (0–15%), medium (15–75%) and high (> 75%) according to Dahiya et al. (1984). Pearson correlation coefficients between cereal grain yield and soil variables for each year and for cereal yield between all study years were calculated.

2.3.2. Geostatistical methods

Analysis of spatial dependence and distribution for each variable was performed using geostatistical methods. Mathematical functions were fitted to the experimentally derived semivariograms that were used for mapping the soil properties and cereal yields by kriging (Gamma Design Software, GS + 9, 2008).

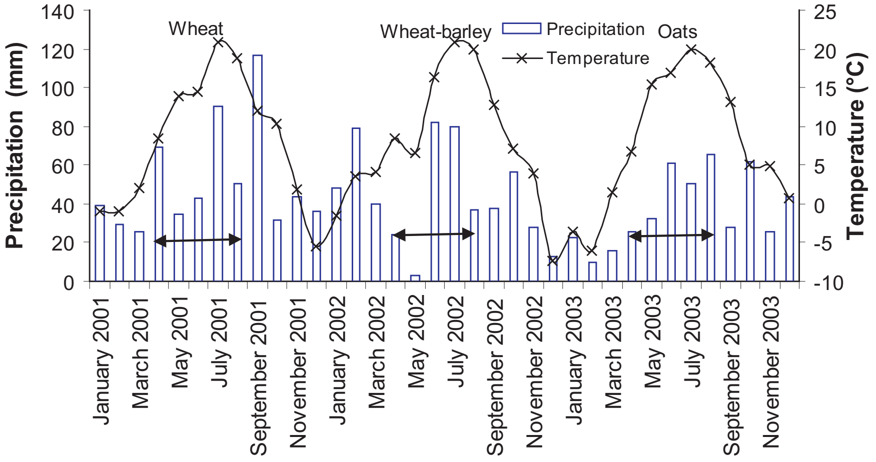

Fig. 1. Monthly precipitation sums and average air temperature in the different study years. Arrow bars indicate months of the growing seasons.

The experimental isotropic semivariogram $\gamma(h)$ and cross-semivariogram $-\gamma_{12}(h)$ for the distance h was calculated from the equations:

$$\gamma(\mathrm{h})=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[z_1(x_i)-z_1(x_i+h)\right]^2$$

$$\gamma_{12}(\mathrm{h})=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[z_1(x_i)-z_1(x_i+h)\right]\cdot\left[z_2(x_i)-z_2(x_i+h)\right]$$

where $N(h)$ is the number of pairs of points with values of $[z_1(x_i), z_1(x_i+h)]$, $[z_2(x_\mathrm{i}), z_2(x_\mathrm{i}+h)]$, distant by h, $z_1(x_i)$ and $z_2(x_i)$ are the values measured at point x_i. Three parameters are distinguished for the semivariogram and cross-semivariograms: the nugget effect, the sill, and the range. When the semi- or cross-semivariograms are increasing functions starting from a certain value rather than zero, the value is named the nugget effect. It tells about the variability of the variable with a scale smaller than the sampling interval and/or accuracy of measurement. The value at which the semi- or cross-semivariogram function reaches saturation (approximately equal to the sample variance) is the sill. The distance from zero to the point where the semi- or cross-semivariogram reach 95% of the sill value is called the range that expresses the greatest distance at which the values samples are auto- or cross-correlated.

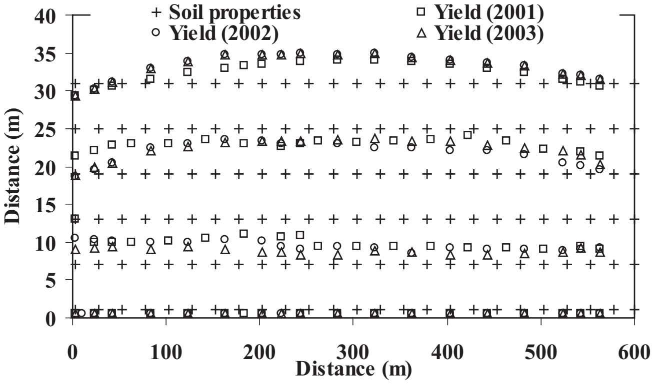

Fig. 2. Sampling points for soil properties and cereal grain yield spring wheat (2001), wheat barley mixture (2002), and oats (2003) in experimental field. The point (0, 0) on a co-ordinate plane corresponds to 0 in lower left corner of the experimental field (framed by a solid line) on the Figs. 3–6.

For semivariograms and cross-semivariograms determined empirically, the following mathematical model was selected using the last squares method (Gamma Design Software, GS + 9, 2008):

- The linear isotropic model:

$$\gamma(\mathrm{h})=C_0+\left[h\left({}^{C}/_{A_0}\right)\right]$$

- The spherical isotropic model:

$$\gamma(h)=\begin{cases}C_0+C\cdot\left[1.5\dfrac{|h|}{A_0}-0.5\left(\dfrac{|h|}{A_0}\right)^3\right] & |h|\le A_0\\ C_0+C & h>A_0\end{cases},$$

- The exponential isotropic model:

$$\gamma(h)=C_0+C\cdot\left[1-e^{-\frac{|h|}{A_0}}\right]\qquad |h>0|$$

- The Gaussian or hyperbolic isotropic model:

$$\gamma(h)=C_0+C\cdot\left[1-e^{-\frac{|h|^2}{A_0^2}}\right]\qquad |h>0|$$

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 linear model, there is no effective range and A is the separation distance (h) for the last lag class graphed in the semivariogram. In the case of the spherical model, the effective range $A = A_0$. In the case of the exponential model, the effective range $A = 3A_0$, which is the distance at which the sill ($C_0 + C$) is within 5% of the asymptote. In the case of the Gaussian model, the effective range $A = 3^{0.5}A_0$, which is the distance at which the sill ($C_0 + C$) is within 5% of the asymptote. The spatial dependences ($C_0/(C_0 + C)$) < 0.25, 0.25–0.75, and > 0.75 are considered strong, moderate, and weak, respectively (Cambardella et al., 1994). The semivariograms for each single studied variable and cross-semivariograms for the paired crop yields and textural fractions, pH, SOC or CEC in the plough and subsoil layers for each study year were calculated.

Estimation of values in places, where no samples have been taken, can be conducted with the help of an estimation method called the ordinary kriging method (Gamma Design Software, GS + 9, 2008):

$$z^*(x_0)=\sum_{i=1}^{N}\lambda_i z(x_i)$$

where N is the number of measurements, $z(x_i)$ is the value measured at point x_i, $z^*(x_o)$ is the estimated value at the point of estimation x_o, and λ_i are weights.

Kriging weights are obtained from the system of equations:

$$\begin{cases} \sum_{j=1}^{N} \lambda_j \gamma(x_i, x_j) + \mu = \gamma(x_i, x_o) & i = 1 \cdots N \\ \sum_{i=1}^{N} \lambda_i = 1 \end{cases}$$

Solving the above system of equations, we determined the kriging weights – λ_i. The weights also allow determination of the estimated function z^* and its variance from the formula:

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

The kriging method was used for drawing 2 D maps.

3. Results

3.1. Basic statistics

Basic statistics including the mean, minimum, maximum, kurtosis, and skewness for soil properties selected in this study are given in Tables 1 and 2. The mean content of inherent sand in the plough layer 0–25 cm (86.0%) was slightly higher (by 2.2%) and that of silt (12%) slightly lower (by 2.1%) than in the subsoil layer (25–40 cm), whereas the clay content was not different in both layers (2–2.2%). Mean SOC and CEC were 0.83% and 11.8 cmol kg^{-1} in the plough layer and lower by 62% and 15%, respectively, in the subsoil. The soil in both layers were acidic (pH 3.9–4.4).

The CV values of the soil properties including textural fractions, SOC, CEC, and pH ranged from 5% for the sand content in the plough layer to 85.6% for SOC in the subsoil. The SOC had medium variability in the plough layer and high variability (CV > 75%) in the subsoil. The skewness of the properties (from −0.24 to 1.3) indicates in general symmetric distribution as indicated by similar the right tail (positive) and left tail (negative) of the curve, except pH (5.4) exhibiting positive asymmetry. The positive kurtosis values indicate a slim peak for the soil properties (from 0.324 to 42.9), except the negative value for sand (−0.325), which suggested close to normal distribution.

Table 1
Basic statistics for soil grain size distribution, pH, organic carbon content (SOC) and cation exchange capacity (CEC) in the experimental field as determined in 2001.

Parameter	% content of grains			pH	SOC	CEC
	Sand 2–0.02 (mm)	Silt 0.02–0.002 (mm)	Clay <0.002 (mm)	–	(%)	(cmol kg^{-1})
Plough layer						
Number of values	150	150	150	150	150	150
Mean	86.0	12.0	2.0	3.91	0.83	11.8
Standard deviation	4.3	4.0	1.4	0.29	0.34	3.6
Coefficient of variation (%)	5.0	32.9	70.0	7.4	41.2	30.5
Minimum	75	2	0	3.56	0.014	3.7
Maximum	97	24	8	6.49	1.800	23.8
Skewness	0.126	0.163	1.29	5.4	0.279	0.634
Kurtosis	−0.325	0.324	2.61	42.9	0.775	0.736
Subsoil layer						
Number of values	150	150	150	150	150	150
Mean	83.8	14.1	2.2	4.4	0.31	10.0
Standard deviation	4.6	4.4	1.2	0.26	0.26	3.42
Coefficient of variation (%)	5.4	30.9	54.5	6.0	85.6	34.3
Minimum	68	1	0	3.85	0.003	3.00
Maximum	97	29	7	5.20	1.227	25.6
Skewness	0.171	−0.236	1.342	0.614	1.046	1.100
Kurtosis	1.347	1.098	3.071	0.514	0.985	2.678

Table 2
Basic statistics for soil water content (TDR), bulk density in plough layer in the experimental field.

Parameters	Spring 2002	Summer 2002	Spring 2003	Summer 2003
Water content (m^3 m^{-3})				
Number of values	150	150	150	150
Mean	0.154	0.141	0.184	0.103
Standard deviation	0.048	0.049	0.038	0.041
Coefficient of variation (%)	31.1	35.1	20.6	39.6
Maximum	0.356	0.316	0.330	0.296
Skewness	1.369	1.326	0.973	2.053
Kurtosis	3.486	3.238	2.617	6.179
Bulk density (Mg m^{-3})				
Number of values	116	130	130	130
Mean	1.302	1.380	1.320	1.406
Standard deviation	0.128	0.095	0.134	0.083
Coefficient of variation (%)	9.8	6.9	10.2	5.9
Minimum	1.025	1.134	1.031	1.178
Maximum	1.575	1.576	1.650	1.584
Skewness	0.158	−0.420	0.101	−0.364
Kurtosis	−0.857	−0.259	−0.715	−0.123

The water content in the plough layer, both in 2002 and in 2003, ranged between 0.154 and 0.184 m^3 m^{-3} in spring and 0.103–0.141 m^3 m^{-3} in summer (Table 2). The corresponding ranges for bulk density were 1.302–1.320 and 1.380–1.406 Mg m^{-3}. Irrespective of the study year and measurement occasion, the water content and bulk density exhibited medium (CV = 20.6–39.6%) and low variability (CV = 5.9–10.2%), respectively (Dahiya et al., 1984). As indicated by the skewness values, the soil water content data exhibited slightly positive asymmetry (0.973–2.053), whereas for the bulk density it was positive (0.101–0.158) in spring and negative in summer (−0.41 to −0.364) in all study years. The kurtosis values indicate a slim peak for the soil water content (2.6 to 6.2) and a slightly flat peak for bulk density (−0.857 to −0.123). These indicate the bulk density values, compared to the soil water content data, were closer to normal distribution for which skewness and kurtosis are near zero.

The mean cereal grain yield ranged from 0.168 (in 2001) to 0.281 kg m^{-2} (in 2003) (Table 3). Both minimum and maximum values were the largest in 2003. The CV was medium and ranged from 27.0% in 2003 to 45.5% in 2001. The asymmetry (skewness) of the yields decreased in the successive years from positive 1.494 to negative (−0.204) values. The kurtosis showed flattening of the distribution in 2002 and 2003 (0.467–0.536), compared to 2001 (2.821). These indicate that the yield in 2002 was the closest to the normal distribution.

Table 4 presents linear correlation coefficients (r) between selected soil properties and cereal grain yield at $p < 0.05$ in the three study years. In 2001, the grain wheat yield was significantly and positively correlated with pH both in the plough layer and subsoil ($r = 0.590$ and 0.556). In 2002, the yield was negatively correlated with the sand content in the plough and subsoil layers ($r = -0.316$ and $-$ 0.275) and

Table 3
Basic statistics for cereal yields in the experimental field.

Parameters	Cereal yield (kg m^{-2})		
	Wheat (2001)	Wheat+barley (2002)	Oats (2003)
Number of values	72	72	72
Mean	0.168	0.188	0.281
Standard deviation	0.076	0.052	0.076
Coefficient of variation (%)	45.5	27.9	27.0
Minimum	0.054	0.055	0.074
Maximum	0.438	0.325	0.485
Skewness	1.494	0.143	−0.204
Kurtosis	2.821	0.467	0.536

Table 4
Correlation coefficients (r) between cereal grain yield and soil variables and for cereal yield between the study years.

	Variables	2001 Wheat (kg m^{-2})	2002 Wheat+barley (kg m^{-2})	2003 Oats (kg m^{-2})
Plough layer	Sand, 2–0.02 (mm)	0.110	**−0.316**[a]	−0.127
	Silt, 0.02–0.002 (mm)	−0.130	**0.291**	0.159
	Clay, <0.002 (mm)	0.048	0.146	−0.081
	pH	**0.590**	**0.371**	0.092
	SOC (%)	0.205	0.205	−0.029
	CEC (cmol kg^{-1})	0.226	**0.271**	0.050
Subsoil layer	Sand, 2–0.02 (mm)	0.116	**−0.275**	0.000
	Silt, 0.02–0.002 (mm)	−0.124	0.236	0.007
	Clay, <0.002 (mm)	−0.030	0.222	−0.016
	pH	**0.556**	0.231	0.153
	SOC (%)	0.021	0.078	0.066
	CEC (cmol kg^{-1})	−0.087	0.225	0.039
Plough layer				
Spring	Water content TDR (m^3 m^{-3})		0.245	0.068
	Bulk density (Mg m^{-3})		−0.040	−0.059
Summer	Water content TDR (m^3 m^{-3})		**0.389**	0.120
	Bulk density (Mg m^{-3})		−0.128	0.207
Year				
2001	Wheat yield (kg m^{-2})	1.000	**0.517**	**0.342**
2002	Wheat+barley yield (kg m^{-2})		1.000	**0.598**
2003	Oats yield (kg m^{-2})			1.000

SOC, soil organic carbon; CEC, cation exchange capacity.

[a] Correlation coefficients in bold are significant at the $p < 0.05$).

positively correlated with the silt content, pH, and CEC ($r = 0.291$, 0.371 and 0.271) in the plough layer. However, there were no significant relationships between the yield and the above soil properties in 2003. The water content in summer 2002 was significantly correlated with the cereal yield ($r = 0.389$). It is worth stressing that the cereal yields among all study years were positively correlated ($r = 0.342$ to 0.598), which indicates inter-annual similarity in their spatial distribution.

3.2. Geostatistical analysis

3.2.1. Semivariograms

The distributions of most variables except the pH in the plough layer and the clay content in both layers were similar to the normal distribution and hence met the condition of a stationary or quasi-stationary process (Tables 1–3 and 5). This condition was met when the skewness was close to zero and the sill was similar for semivariance and classical variance. The normality for the pH and clay content was obtained after log-natural transformation. The exponential, spherical, and linear models were adjusted to 18, 3, and 2 variables, respectively (Table 5) with a satisfactory accuracy ($R^2 > 0.6$, data not shown). The largest nugget effects (C_0) indicating irregular and discontinuous distribution were noted in the sand and silt contents in both plough and subsoil layers (9.9–14.4) and they were substantially lower or null for all the other soil properties and crop yields (0.00–0.0881). The sills ($C_0 + C$) had the largest values in both layers for the sand and silt contents (15.45–20.50), CEC (11.14–12.71), and clay content (0.1596–1.92) and the lowest values for the water content in both spring and summer (0.00088–0.00135).

The values of the nugget to sill ratio show that the spatial dependence was very strong (<0.25) or moderate (0.25–0.75) for most soil properties and cereal yields, except for bulk density in spring in both 2002 and 2003 with weak spatial dependence (>0.75) (Cambardella et al., 1994).

The effective ranges of spatial dependencies (A) varied from 10.5 m for SOC in the subsoil layer to 373.4 m for bulk density in the plough layer in summer 2003. The ranges for the contents of all soil textural fractions (except sand), pH, SOC, and CEC were greater in the plough than subsoil layer. The spatial pattern of SWC showed a similar range of spatial dependence in spring and summer 2002 (59.4–61.5 m), whereas in 2003 it increased from 18.0 m in spring up to 205 m in summer. The same range of spatial dependence was noted for the bulk density in spring in both study years (325.4 m), whereas in summer it was greater in 2003 (373.4 m) than in 2002 (33.0 m). The range for the cereal grain yields during the three-year period varied from 24.3 to 58.5 m (Table 5).

Table 5
Semivariogram coefficients of soil properties and cereal yields.

Semivariogram	Variables	Model	Nugget, C_0 (unit)^2	Sill, $C_0 + C$ (unit)^2	Nugget ratio, $C_0/(C_0 + C)$	Range, A (m)
Plough layer	2–0.02 (mm)	Exp.	10.5	18.45	0.568	200.0
	0.02–0.002 (mm)	Exp.	9.9	15.45	0.641	200.0
	<0.002 (mm)	Exp.	0.0010	1.92	0.001	36.0
	pH	Exp.	0.0074	0.0873	0.085	41.1
	SOC (%)	Exp.	0.0001	0.1152	0.001	23.7
	CEC (cmol kg^{-1})	Exp.	0.01	12.71	0.001	34.5
Subsoil layer	2–0.02 (mm)	Exp.	14.4	20.50	0.702	220.0
	0.02–0.002 (mm)	Exp.	12.9	18.55	0.697	150.0
	<0.002 (mm)	Exp.	0.0881	0.1596	0.552	25.4
	pH	Exp.	0.0001	0.0624	0.002	28.8
	SOC (%)	Exp.	0.0088	0.0671	0.131	10.5
	CEC (cmol kg^{-1})	Sph.	0.01	11.14	0.001	23.6
Year 2002	Plough layer					
Spring	Water content TDR (m^3 m^{-3})	Exp.	0.00000	0.00144	0.001	59.4
	Bulk density (Mg m^{-3})	Lin.	0.01634	0.01634	1.000	325.4
Summer	Water content TDR (m^3 m^{-3})	Exp.	0.00000	0.00135	0.001	61.5
	Bulk density (Mg m^{-3})	Exp.	0.00136	0.00932	0.146	33.0
Year 2003	Plough layer					
Spring	Water content TDR (m^3 m^{-3})	Exp.	0.00000	0.00099	0.003	18.0
	Bulk density (Mg m^{-3})	Lin.	0.01676	0.01676	1.000	325.4
Summer	Water content TDR (m^3 m^{-3})	Sph.	0.00044	0.00088	0.499	205.0
	Bulk density (Mg m^{-3})	Sph.	0.00432	0.00865	0.499	373.4
Years						
2001	Wheat yield (kg m^{-2})	Exp.	0.00006	0.00499	0.012	45.9
2002	Wheat-barley yield (kg m^{-2})	Exp.	0.00003	0.00256	0.010	58.5
2003	Oats yield (kg m^{-2})	Exp.	0.00012	0.00498	0.025	24.3

Exp. – exponential, Sph. – spherical, Lin. – linear, C_0 – nugget variance, $C_0 + C$ – sill, A – effective range.

3.2.2. Cross-semivariograms

The experimental values were best fitted mostly to the Gaussian (20), spherical (7), exponential (6), and linear (3) models (Table 6). The cross-semivariogram models showed that the nugget effect (C_0) values were in general rather low (−0.032–0.0139) with the values of sill ($C_0 + C$) from −0.224 to 0.2378. The most consistent relationship between the crop yield and soil properties was the positive correlation between cereal yield and pH, silt content and CEC and the negative relationship between the yield and sand content. The nugget to sill ratio ($C_0/(C_0 + C)$) exhibited strong, moderate, and weak spatial interdependence (Cambardella et al., 1994) of paired variables in 31, 3, and 2 cases, respectively. The range of the spatial interdependence varied from 24.8 m to up to 2433 m, which is about four times greater than the length of the experimental field.

The cross-semivariogram analysis demonstrated a positive relationship of the cereal yield and water content in all years, indicating that both variables are associated (Table 6). However, the cross-semivariograms of the cereal yield and soil bulk density were negatively or positively spatially dependent, except in spring 2003 when a pure nugget effect (C_0) was observed. The cross-semivariograms of the cereal yields between the studied years were positive with a considerably larger range for the crop yield 2001 × 2003 (1404.0 m) than those for 2001 × 2002 and 2002 × 2003 (28.2–42.3 m).

Table 6
Cross-semivariograms parameters of soil properties and crop yields.

	Variables	Model	Nugget, C_0 (unit)^2	Sill, $C_0 + C$ (unit)^2	Nugget ratio, $C_0/(C_0 + C)$	Range, A (m)
Plough layer	Year 2001					
	Yield_Sand	Exponential	0.00001	0.03042	0.000	120.3
	Yield_Silt	Gaussian	−0.00001	−0.03092	0.000	64.1
	Yield_Clay	Gaussian	0.00000	0.00230	0.000	67.6
	Yield_pH	Exponential	0.00025	0.00544	0.046	112.5
	Yield_SOC	Gaussian	0.00001	0.00366	0.003	162.8
	Yield_CEC	Gaussian	0.00001	0.02572	0.000	134.6
	Year 2002					
	Yield_Sand	Exponential	−0.03200	−0.07530	0.425	1104.9
	Yield_Silt	Exponential	0.01520	0.09300	0.163	2432.7
	Yield_Clay	Gaussian	0.00001	0.01722	0.001	90.9
	Yield_pH	Spherical	0.00000	0.00163	0.001	54.6
	Yield_SOC	Gaussian	0.00000	0.00176	0.001	102.2
	Yield_CEC	Gaussian	0.00010	0.04140	0.002	85.4
	Year 2003					
	Yield_Sand	Gaussian	−0.00700	−0.22400	0.031	959.7
	Yield_Silt	Gaussian	0.01390	0.23780	0.058	1045.1
	Yield_Clay	Linear	−0.00088	−0.00088	1.000	325.4
	Yield_pH	Gaussian	0.00001	0.00480	0.002	1044.1
	Yield_SOC	Linear	−0.00046	−0.00046	1.000	325.4
	Yield_CEC	Gaussian	0.00010	0.15970	0.001	1067.3
Subsoil layer	Year 2001					
	Yield_Sand	Spherical	−0.01610	−0.05640	0.285	273.9
	Yield_Silt	Gaussian	0.01280	0.04670	0.274	272.8
	Yield_Clay	Spherical	0.00001	0.01202	0.001	53.6
	Yield_pH	Exponential	0.00000	0.00231	0.000	126.9
	Yield_SOC	Gaussian	0.00000	−0.00076	0.001	416.9
	Yield_CEC	Spherical	0.00150	0.03650	0.041	53.2
	Year 2002					
	Yield_Sand	Gaussian	−0.00001	−0.02892	0.000	1179.9
	Yield_Silt	Linear	0.00001	0.01892	0.001	120.0
	Yield_Clay	Gaussian	−0.00057	−0.01184	0.048	32.6
	Yield_pH	Exponential	0.00720	0.05010	0.144	370.2
	Yield_SOC	Gaussian	0.00000	−0.00150	0.001	1322.2
	Yield_CEC	Spherical	−0.00001	−0.02762	0.000	94.3
	Year 2003					
	Yield_Sand	Gaussian	−0.00010	−0.10470	0.001	771.3
	Yield_Silt	Gaussian	0.00010	0.09820	0.001	810.1
	Yield_Clay	Spherical	0.00000	−0.00010	0.001	24.8
	Yield_pH	Gaussian	0.00029	0.01355	0.021	1156.8
	Yield_SOC	Spherical	0.00000	0.00136	0.001	53.8
	Yield_CEC	Gaussian	0.00001	0.02742	0.000	342.8
Year 2002	Plough layer					
Spring	Yield_Water content	Gaussian	0.00000	0.00040	0.002	59.8
	Yield_Bulk density	Gaussian	0.00000	0.00302	0.000	1404.5
Summer	Yield_Water content	Spherical	0.00002	0.00042	0.050	127.1
	Yield_Bulk density	Spherical	0.00000	−0.00078	0.001	30.1
Year 2003	Plough layer					
Spring	Yield_Water content	Gaussian	0.00000	0.00210	0.000	1028.0
	Yield_Bulk density	Linear	−0.00047	−0.00047	1.000	325.5
Summer	Yield_Water content	Gaussian	0.00000	0.00210	0.000	1114.6
	Yield_Bulk density	Gaussian	0.00047	0.01838	0.026	1404.5
Years						
2001/2002	Yield Wheat_Wheat+barley	Exponential	0.00000	0.00165	0.001	42.3
2001/2003	Yield Wheat_Oats	Gaussian	0.00111	0.01315	0.084	1404.0
2002/2003	Yield Wheat+barley_Oats	Exponential	0.00000	0.00208	0.000	28.2

C_0 is the nugget variance, $C_0 + C$ is the sill, A – effective range. Yield (wheat – 2001, wheat+barley – 2002, oats – 2003) is in kg m^{-2}, Sand (2–0.02 mm), Silt (0.02–0.002 (mm) and Clay (<0.002 mm), Soil organic carbon (SOC) are in %, Cation exchange capacity (CEC) in cmol kg^{-1}, Water content in m^3 m^{-3}, and Bulk density in Mg m^{-3}.

3.3. Kriging maps

Maps of the soil properties and cereal yield were preliminarily drawn using ordinary kriging and co-kriging methods. The results were similar in both methods and, therefore, we used ordinary kriging based on semivariogram models (Table 5). The spatial patterns of sand, silt, and clay contents, SOC, CEC, and SWC were reflected in the patterns of cereal yields in all study years (Figs. 3–5). Also the spatial patterns of the cereal yield among the study years were similar (Fig. 5). Analysis of the maps indicates that, both in the plough layer and in the subsoil, the rightmost part of the field (approx. 400–500 m) has more sand whereas the middle and left parts of the field – more silt. The higher silt content in the plough layer in the middle left part of the field corresponds with the higher CEC and SOC.

The soil water content was much more variable in 2003 than in the growing season 2001. The higher soil water content in both spring and summer 2003 in the middle and left parts of the field corresponds with the higher silt and clay contents and cereal yield. In contrast, the rightmost part of the field had more sand and lower water content and cereal yield. The whole field soil had acid reaction of pH <4.4 (Fig. 3) displaying low variability (CV 6.0–7.4%) in both the plough and subsoil layers (Table 1).

4. Discussion

4.1. Semivariogram and cross-semivariogram parameters

The variances defined in the classical way (standard deviation^2) in comparison to the semivariance equals the sill value ($C_0 + C$) for the data of variables studied were similar, which indicates the lack of a clear spatial trend and that further spatial analyses can be conducted without trend removal. The model parameters of direct and cross-semivariograms were appreciably different, irrespective of the adjusted type of the model, (Tables 5–6). The smaller nugget values (C_0) in the cross- compared to direct semivariograms indicate smoother spatial continuity and dependency between adjacent sampling points (Jabro et al., 2010; Paz-Ferreiro et al., 2010; Vieira and Gonzalez, 2003). Furthermore, this implies a smaller nugget effect in the cross-semivariograms, compared with direct semivariograms, leading to reduction of short-scale variability when the influence of other variables

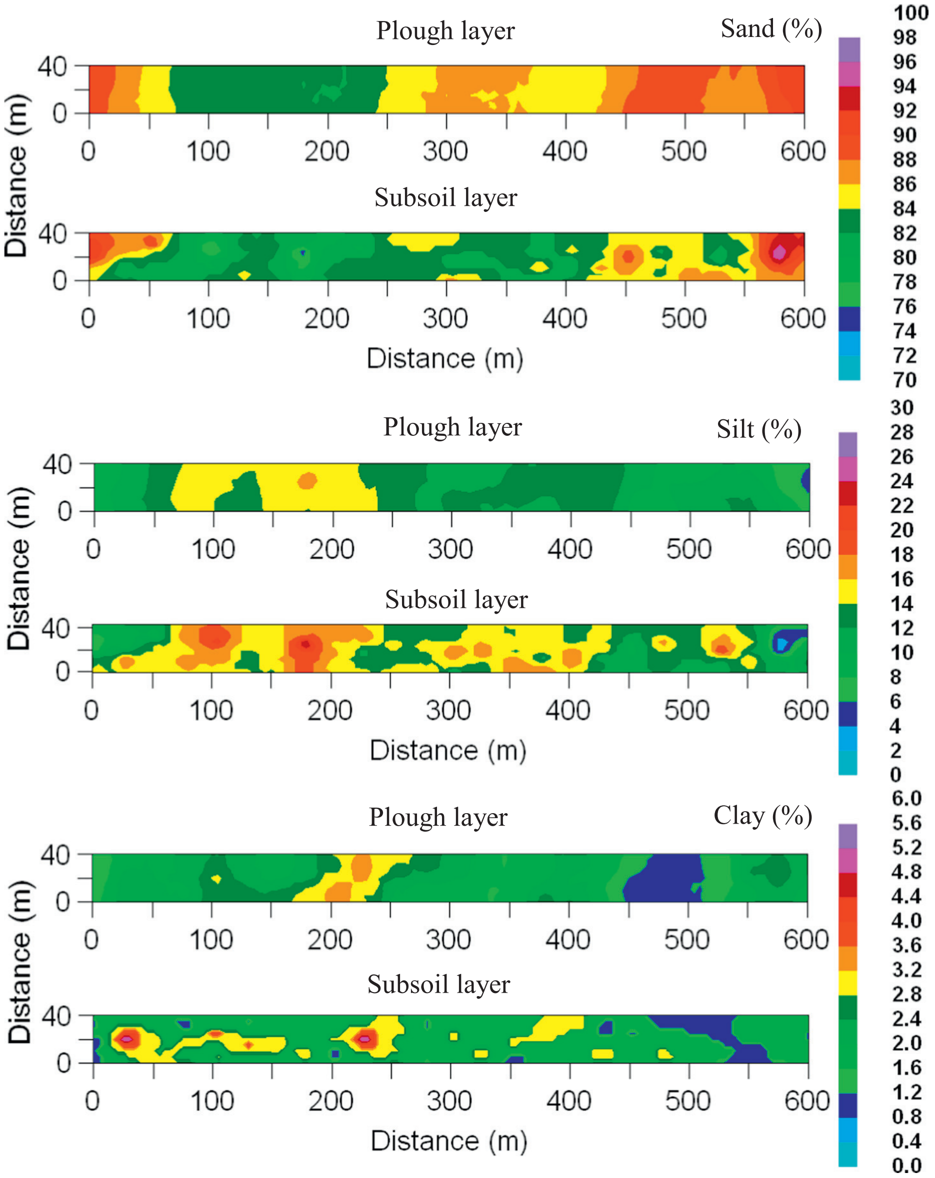

Fig. 3. Maps of sand, silt and clay content, pH, soil organic carbon (SOC) and cation exchange capacity (CEC) for plough and subsoil layers in the experimental field.

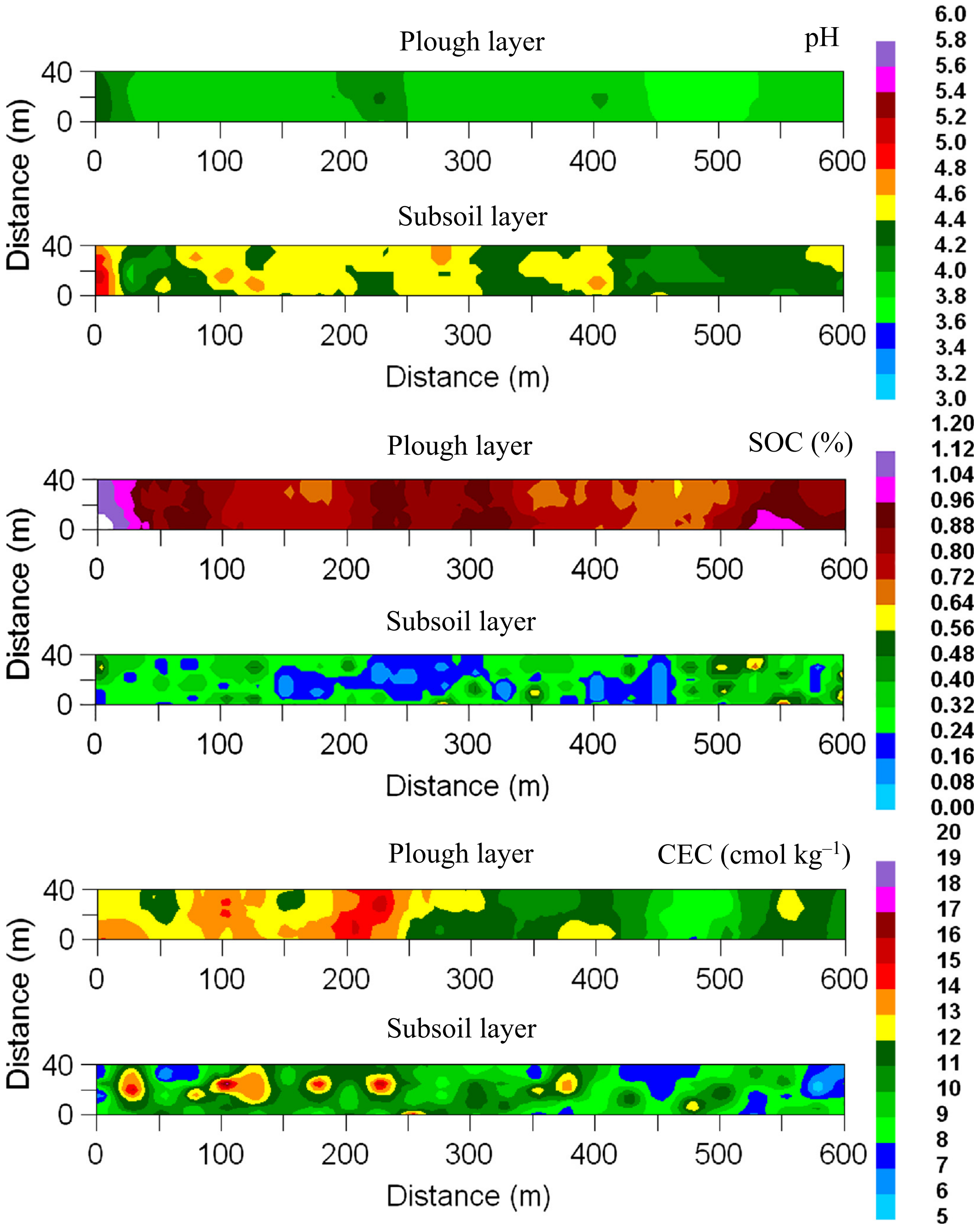

Fig. 3 (*continued*).

and their measurement errors are considered (Millán et al., 2012). The nugget to sill ratio values in a majority of direct semivariograms (14 out 23) and cross-semivariograms (32 out 36) were smaller than 0.25 indicating strong spatial dependence (Cambardella et al., 1994; Jabro et al., 2010).

The strong positive dependence between the cereal yield and SWC in spring 2002 coincided with the similar range of the cross-semivariogram, i.e. 59.8 m, and respective ranges in the direct semivariograms for the above variables, i.e. 58.5 and 59.4 m (Tables 5–6). This demonstrates well-defined co-variability structures of the paired variables and implies that the soil water content at the beginning of the growing season had a significant effect on the spatial distribution of the cereal yield. However, the absence of such similarity between the other paired variables may be related to the relatively small spatial scale in our study, but may occur on greater spatial scales (Gutiérrez-López et al., 2010). It should be underlined that the range values of direct semivariograms are smaller than in cross-semivariograms (Tables 5–6). In the case of two pairs, i.e. the crop yield and silt content and the crop yield and sand content, the ranges (960–2463 m) were greater than the field dimensions (600 × 40 m). This indicates that the textural fractions can affect cereal yields, probably by an opposite indirect effect of silt and sand on the SOC content and the related different water and nutrient availability (Galantini et al., 2004).

4.2. Effect of weather conditions

It is worth noting that the lowest mean cereal yield in 2001 surprisingly corresponds with the highest total rainfall amount (404 mm) during the growing season (April–September), whereas the greater grain yield in 2002 and 2003 corresponds with lower precipitations during the growing season (263–285 mm) (Table 3, Fig. 1). This can be explained by the different weather conditions prevailing during the growing season. The largest crop yield in 2003 can be mostly due to the relatively high temperature and suitable distribution of rainfall amounts in May–June, which is a critical period for cereal growth in Poland (Skowera et al., 2015). However, the positive relationship between the yield and soil water content in summer 2002 ($r = 0.389$) supports the significant contribution of water supply to cereal yields grown on sandy soil of low water holding capacity (Łabędzki and Bąk, 2017; Minasny and Mc Bratney, 2018). This relationship can be a consequence of the relatively high rainfalls in June–July. Therefore, these results indicate that in sandy soils with low water holding capacity the cereal yields depend not only on the total amount of rainfall, but even to a greater extent on its temporal distribution as related to stage of plant growth.

The analysis of results obtained from classical and geostatistical methods allowed us to show different direction and the impact of a particular soil variable on the grain yield depending on the weather conditions. The interactive effect of textural fractions and weather was visible by comparison a negative relationship between the silt content and the grain yield under wetter conditions in 2001 and positive under drier conditions in 2002–2003 (Tables 3 and 4). In some cases, the classic simple correlations between the selected soil properties and the cereal yield were not significant e.g. between SWC and the yield in 2003 and in spring 2002, which can be related to the limited number of data (72). However, in the case of spatial cross-correlations, the number increases due to inclusion of the interactions between the paired variables at different distances up to several thousands and thus reinforcing the strength of the statistical analysis and the conclusions about the impact and direction of a given variable on the crop yield.

Our results showed that the soil bulk density in spring in both years shows random spatial distribution, as indicated by the pure nugget effect in the linear model (Table 5). This may result from the pre-sowing tillage operations just before sampling that align bulk density in the plough layer. However, occurrence of spatial dependence in bulk density at harvest time (in summer), as described by the spherical or exponential models, can be induced by external factors including soil subsidence, rainfalls, and machinery traffic during growing and associated changes in soil structure. The external factors and associated processes are described and explained by the first order autoregression Markov process and/or the Poisson process (Kuzyakova et al., 2001) and the moving average of random processes (Kuzyakova et al., 2001; Millán et al., 2012).

It is worth noting that the ranges of semivariograms for the yield and pH, SOC, and CEC that substantially affect the crop yield in sandy soils are small (10.5–58.5 m). This means that these variables are spatially dependent only across relatively short distances and independent and randomly distributed when the distances are longer. These soil chemical properties were spatially related to the clay content, as indicated by a similar value of the range (25.4–36 m) in contrast to the silt and sand contents having greater ranges.

4.3. Maps of soil properties and cereal yields

The kriging maps revealed that the low cereal yield in our experimental field occurs in a distinct area (approx. 400–500 m). The soil in

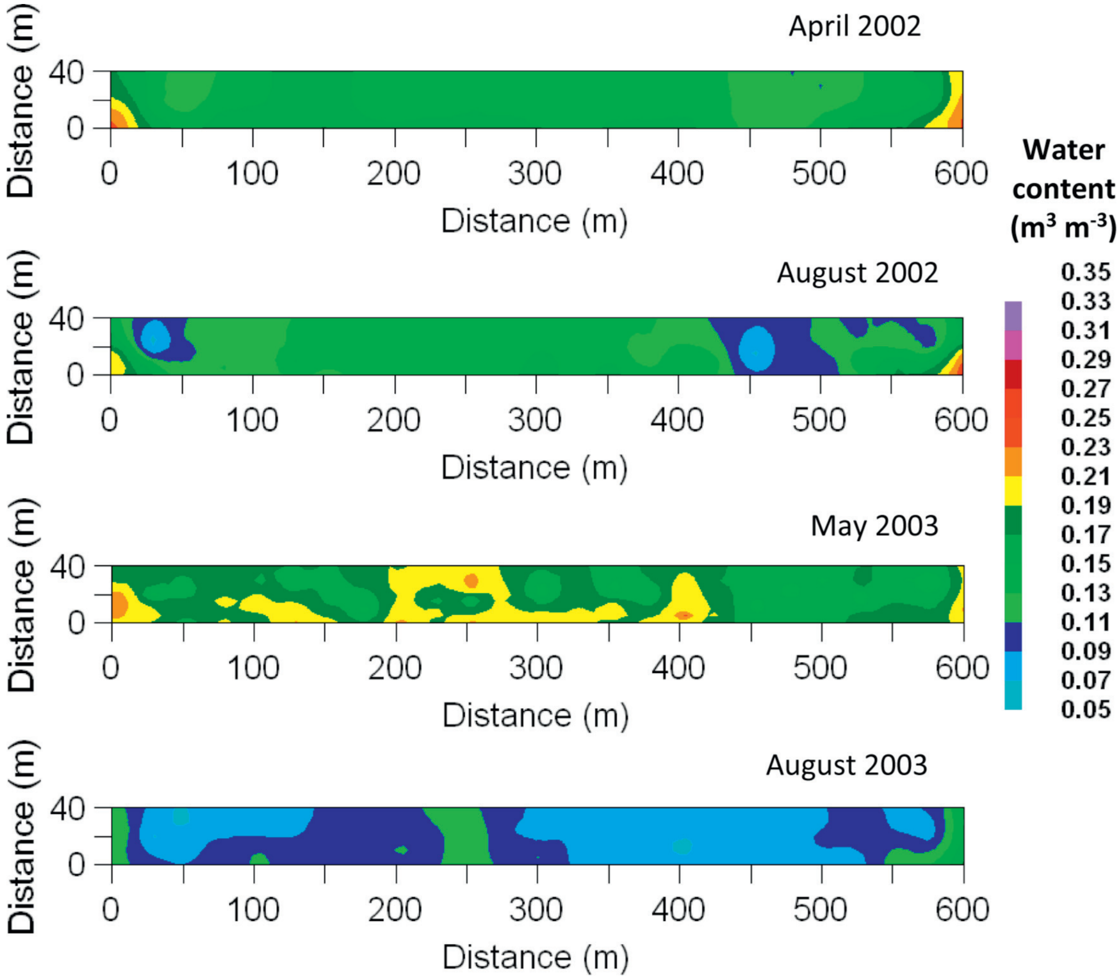

Fig. 4. Maps of soil water content (TDR) and bulk density for plough layer in the experimental field.

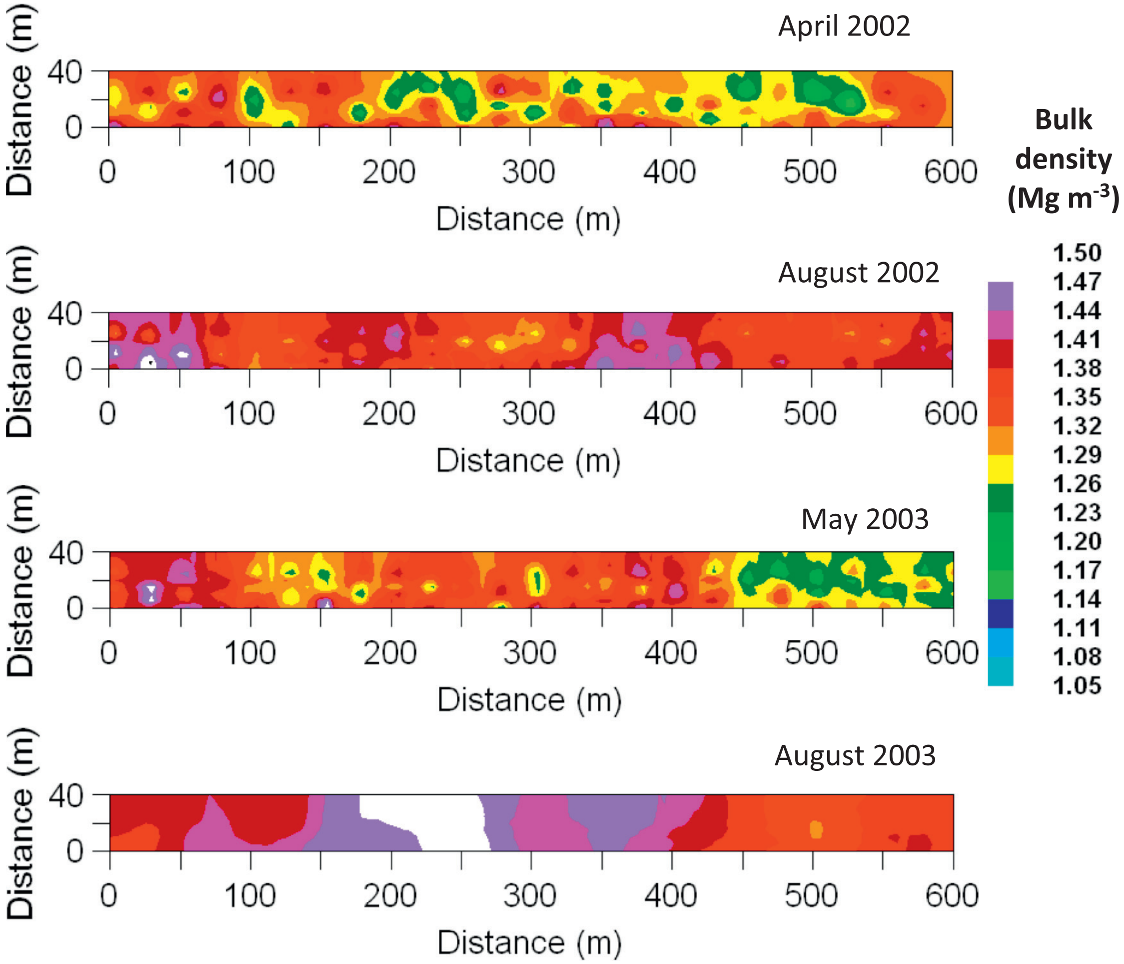

Fig. 4 (*continued*).

the low-yielding area has the lowest CEC, SOC content, and pH in both the plough and subsoil layers. This implies that the yield reduction in this area can be induced by limited accessibility of water and nutrients associated with the lower CEC and SOC and limited root growth due to the low pH value. This effect may be enhanced by the slight sloping in this area and resulting losses of water and nutrients due to surface

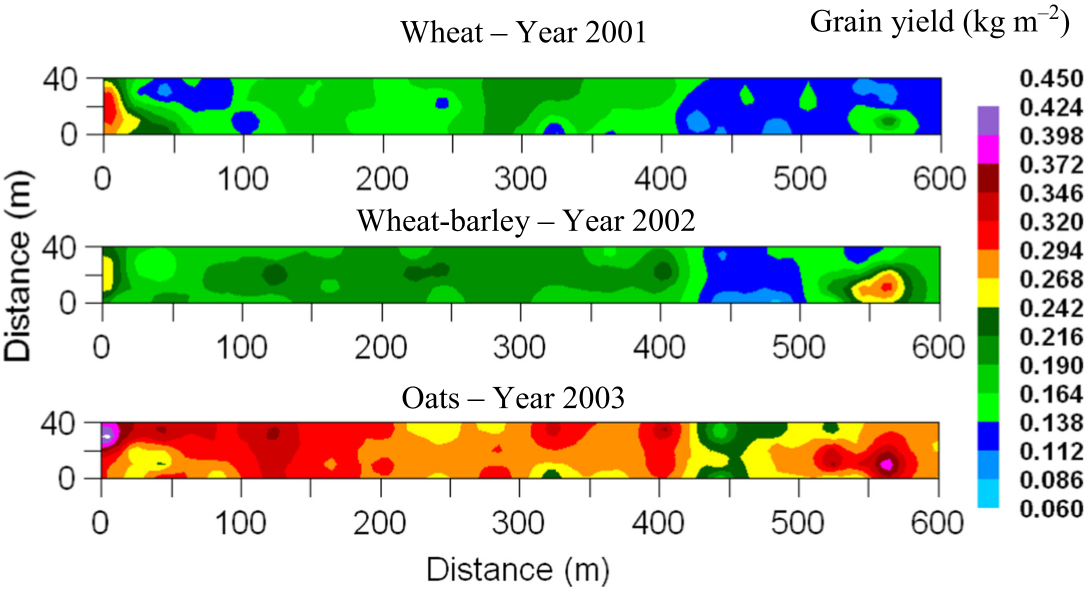

Fig. 5. Maps of cereal grain yield in the experimental field.

Fig. 6. Aerial photo of the experimental field (solid line) and lightened zone (dotted line) including parts of the experimental and neighboring fields. The zone framed by dotted line was partly under plant cover that masks the lightened area. Source: 2016 CNES/Airbus, Digital Google Maps, Poland. The point 0 in lower left corner of the experimental field corresponds to 0, 0 on a co-ordinate plane on the Figs. 2–5.

runoff. An important factor contributing to the unfavourable levels of the soil variables in this distinct area can be the higher content of intrinsic and originally acid sand and its low specific surface area limiting the retention of SOC and CEC and availability of nutrients (Stawiński et al., 2000; Galantini et al., 2004). Field-scale differentiation of the sand content can be related with spatially different glacial processes (Krasowicz et al., 2011; Woronko and Pochocka-Szwarc, 2013).

It is worth noting that this distinct area within our experimental field (Fig. 3) along with the neighboring agricultural fields is seen on the aerial photograph as one similar larger zone separated by lighter color (in SE direction) (Fig. 6). The lighter soil color can be a resultant of high content of the sand (quartz) fraction and low SOC, coloring the soil white and in dark, respectively (Dwivedi, 2017; Vodyanitskii and Savichev, 2017). This implies that the kriging map derived in this study along with larger scale aerial photographs can help in upscale application of soil improving cropping systems (e.g. liming, organic fertilization) leading to greater SOC sequestration. This application can be further justified by our results indicating that the reduction of the cereal yield in the distinct zone occurred consistently in each of the three years with different weather conditions. The above analysis underlines the suitability of the spatial cross-correlation between cereal yields and selected soil properties and the suitability of the geostatistical approach with consideration of aerial photograph in separating a management zone characterized by unfavourable levels of several variables occurring concurrently within a single agricultural field. Low crop yields in the distinct zone were observed by local farmers.

Our results indicate that co-regionalization between cereal yields and different soil properties improves the description of spatial dependence and enhances the significance of maps generated with the kriging method (Paz-Ferreiro et al., 2010; Usowicz et al., 2017). This supports the potential usefulness of cross-semivariance data in predicting the spatial distribution of the cereal yield as a primary variable from auxiliary variables e.g. sand content data that have been gathered usually during soil surveys (Fischer et al., 2008).

Overall, the geostatistical approach including semi- and cross-semivariograms and kriging maps has proved to be an effective tool for division of the experimental field into homogeneous small areas with similar cereal yields and some soil properties. This will be useful information for farmers for identification of field areas for localized application of soil improving practices and for further larger-scale studies including visual aerial photographs, which are currently being conducted within the EU program Horizon 2020.

5. Conclusions

The application of the geostatistical approach including basic statistics, direct semivariograms, and cross-semivariograms improved the description of the spatial dependence between cereal yields and selected soil properties on a field scale. The cross-semivariograms and the kriging maps allowed delineating a field area with a low cereal yield and soil CEC, SOC, and pH. The reduced cereal yield in the distinct area was noted consistently in each of the three study years with different weather conditions. The distinct area is characterized by higher sand content and lower silt content, compared to other part of the field. This area in the experimental field along with some neighboring areas is seen on the aerial photographs as one similar zone separated by lighter soil color, probably due to the greater content of sand and the lower content of SOC. This implies that the analysis of the kriging maps together with a larger-scale aerial photographs allows delineating a larger critical zone based on the data of soil textural composition and organic carbon content that are often available in soil databases. In connection with this observation, further more detailed studies on the spatial relationships between crop yields and soil properties and on their usefulness in upscaling were undertaken on a larger scale.

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References

Adamchuk, V.I., Viscarra Rossel, R.A., 2011. Precision agriculture: proximal soil sensing. In: Gliński, J., Horabik, J., Lipiec, J. (Eds.), Encyclopedia of Agrophysics. Springer Dordrecht, Heidelberg, London, New York, pp. 650–656.

Alaoui, A., Lipiec, J., Gerke, H., 2011. A review of the changes in the soil pore system due to soil deformation: a hydrodynamic perspective. Soil Tillage Res. 115–116, 1–15.

Awe, G.O., Reichert, J.M., Timm, L.C., Wendroth, O.O., 2015. Temporal processes of soil water status in a sugarcane field under residue management. Plant Soil 387, 395–411.

Blake, G.R., Hartge, K.H., Klute, A., 1986. Bulk density. Methods of Soil Analysis, 546 Part 1: Physical and Mineralogical Methods-Agronomy Monograph No. 9. ASA-SSSA 547, pp. 363–375 (Madison, Wisconsin, USA).

Bogunovic, I., Mesic, M., Zgorelec, Z., Jurisic, A., Bilandzija, D., 2014. Spatial variation of soil nutrients on sandy-loam soil. Soil Tillage Res. 144, 174–183.

Bölenius, E., Stenberg, B., Arvidsson, J., 2017. Within field cereal yield variability as affected by soil physical properties and weather variations – a case study in east central Sweden. Geoderma Reg. 11, 96–103.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.L., Turco, R.F., Konopka, A.E., 1994. Field-scale variability of soil properties in Central Iowa soils. Soil Sci. Soc. Am. J. 58, 1501–1511.

Dahiya, I.S., Ritcher, J., Mark, P.S., 1984. Soil spatial variability: review. Int. J. Trop. Agric. 11, 1–102.

Diacono, M., Rubino, P., Montemurro, F., 2013. Precision nitrogen management of wheat. A review. Agron. Sustain. Dev. 33, 219–241.

Dwivedi, R.S., 2017. Remote Sensing of Soils. Springer-Verlag GmbH 500 pp. https://doi.org/10.1007/978-3-662-53740-4.

Fischer, G.F., Nachtergaele, S., Prieler, H.T., van Velthuizen, L., Verelst, D. Wiberg, 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Gajda, A.M., Czyż, E.A., Dexter, A.R., 2016. Effects of long-term use of different farming systems on some physical, chemical and microbiological parameters of soil quality. Int. Agrophys. 30, 165–172.

Galantini, J.A., Senesi, N., Brunetti, G., Rosell, R., 2004. Influence of texture on organic matter distribution and quality and nitrogen and sulphur status in semiarid Pampean grassland soils of Argentina. Geoderma 123, 143–152.

Gilliam, F.S., Dick, D.A., 2010. Spatial heterogeneity of soil nutrients and plant species in herb-dominated communities of contrasting land use. Plant Ecol. 209, 83–94.

Goovaerts, P., 1999. Geostatistics in soil science: state-of-the-art and perspectives. Geoderma 89, 1–45.

Gutiérrez-López, M., Jesús, J.B., Trigo, D., Fernández, R., Novo, M., Díaz-Cosín, D.J., 2010. Relationships among spatial distribution of soil microarthropods, earthworm species and soil properties. Pedobiologia 53, 381–389.

Hedley, C.B., Yule, I.J., 2009. Soil water status mapping and two variable-rate irrigation scenarios. J. Prec. Agric. 10, 1385–2256.

ISO, 1995. International Organization for Standardization 13536: Soil Quality – Determination of the Potential Cation Exchange Capacity and Exchangeable Cations Using Barium Chloride Solution Buffered at pH (7 pp.).

IUSS Working Group W.R.B., 2015. World Reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jabro, J.D., Stevens, W.B., Evans, R.G., Iversen, W.M., 2010. Spatial variability and correlation of selected soil properties in the Ap horizon of a CRP grassland. Appl. Eng. Agric. 2010 (26), 419–428.

Jankowski, M., Przewoźna, B., Bednarek, R., 2011. Topographical inversion of sandy soils due to local conditions in Northern Poland. Geomorphology 135, 277–283.

Kędzior, M.A., Zawadzki, J., 2016. Comparative study of soil moisture estimations from SMOS satellite mission, GLDAS database, and cosmic-ray neutrons measurements at COSMOS station in Eastern Poland. Geoderma 283, 21–31.

Krasowicz, S., Oleszek, W., Horabik, J., Dębicki, R., Jankowiak, J., Stuczyński, T., Jadczyszyn, J., 2011. Rational management of the soil environment in Poland. Pol. J. Agron. 7, 43–58.

Kumhálová, J., Matějková, Š., 2017. Yield variability prediction by remote sensing sensors with different spatial resolution. Int. Agrophys. 31:195–202. https://doi.org/10.1515/intag-2016-0046.

Kuzyakova, I.F., Romanenkov, V.A., Kuzyakov Ya, V., 2001. Geostatistics in soil agrochemical studies. Eurasian Soil Sci. 34 (9), 1011–1017.

Łabędzki, L., Bąk, B., 2017. Impact of meteorological drought on crop water deficit and crop yield reduction in Polish agriculture. J. Water Land Dev. 34 (VI-IX):181–190. https://doi.org/10.1515/jwld-2017-0052.

Malicki, M., 1990. A reflectometric (TDR) meter of moisture content in soils and other capillary porous materials. Zesz. Probl. Postep. Nauk. Rol. 388, 107–114.

Millán, H., Tarquís, A.M., Pérez, L.D., Mato, J., González-Posada, M., 2012. Spatial variability patterns of some vertisol properties at a field scale using standardized data. Soil Tillage Res. 120, 76–84.

Minasny, B., Mc Bratney, A.B., 2018. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 69:39–47. https://doi.org/10.1111/ejss.12475.

Moradi, F., Moosavi, A.A., Moghaddam, B.K., 2016. Spatial variability of water retention parameters and saturated hydraulic conductivity in a calcareous Inceptisols (Khuzestan province of Iran) under sugarcane cropping. Arch. Agron. Soil Sci. 62 (12):1686–1699. https://doi.org/10.1080/03650340.2016.1164308.

Mubarak, I., Janat, M., Makhlouf, M., Hamdan, A., 2016. Rapid selection of a representative monitoring location of soil water content for irrigation scheduling using surface moisture-density gauge. Int. Agrophys. 2016 (30):483–491. https://doi.org/10.1515/intag-2016-0022.

Ostrowska, S., Gawliński, Z., Szczubiałka, Z., 1991. Procedures for Soil and Plant Analysis. Institute of Environmental Protection, Warsaw, Poland (in Polish).

Ozpinar, S., Ozpinar, A., 2015. Tillage effects on soil properties and maize productivity in western Turkey. Arch. Agron. Soil Sci. 61, 1029–1040.

Paz-Ferreiro, J., Vázquez, E.V., Miranda, J.G.V., 2010. Assessing soil particle-size distribution on experimental plots with similar texture under different management systems using multifractal parameters. Geoderma 160 (1), 47–56.

Pedrera-Parrilla, A., Brevik, E.C., Giráldez, J.V., Vanderlinden, K., 2016. Temporal stability of electrical conductivity in a sandy soil. Int. Agrophys. 30:349–357. https://doi.org/10.1515/intag-2016-0005 0.4. 2016.

Sadler, E.J., Evans, R.G., Stone, K.C., Camp, C.R., 2005. Opportunities for conservation with precision irrigation. J. Soil Water Conserv. 60, 371–379.

Schjønning, P., Heckrath, G., Christensen, B.T., 2009. Threats to soil quality in Denmark. A Review of Existing Knowledge in the Context of the EU Soil Thematic Strategy. DJF Report Plant Sci. No. 143. Aarhus University, p. 121.

Schwen, A., Zimmermann, M., Bodner, G., 2014. Vertical variations of soil hydraulic properties within two soil profiles and its relevance for soil water simulations. J. Hydrol. 516, 169–181.

Skowera, B., Kopcińska, J., Kołodziejczyk, M., Kopeć, B., 2015. Precipitation deficiencies and excess during the growing season of winter rape and winter wheat in Poland (1971–2010). Acta Agrophysica 22, 193–207.

Gamma Design Software, 2008. GS. Geostatistics for the Environmental Sciences.

Stawiński, J., Gliński, J., Ostrowski, J., Stępniewska, Z., Sokołowska, Z., Bowanko, G., Józefaciuk, G., Księżopolska, A., Matyka-Sarzyńska, D., 2000. Spatial characterization of specific surface area of arable soils in Poland. Acta Agrophys. Mongr. 33, 1–48.

Usowicz, B., Lipiec, J., 2017. Spatial variability of soil properties and cereal yield in a cultivated field on sandy soil. Soil Tillage Res. 174, 241–250.

Usowicz, B., Lipiec, J., Ferrero, A., 2009. Thermal properties in relation to soil water status in sloping vineyard. Teka Kom. Ochr. Kszt. Srod. Przyr. – OL PAN. 6, pp. 386–410.

Usowicz, B., Łukowski, M., Rüdiger, C., Walker, J.P., Marczewski, W., 2017. Thermal properties of soil in the Murrumbidgee River catchment (Australia). Int. J. Heat Mass Transf. 115PB, 604–614.

Vieira, S.R., Gonzalez, A.P., 2003. Analysis of the spatial variability of crop yield and soil properties in small agricultural plots. Bragantia Campina. 62, pp. 127–138.

Vodyanitskii, Yu.N., Savichev, A.T., 2017. The influence of organic matter on soil color using the regression equations of optical parameters in the system CIE-L*a*b*. Ann. Agric. Sci. 15, 380–385.

Walter, A., Spies, H., Terjung, S., Kusters, R., Kirchgessner, N., Schurr, U., 2002. Spatio-temporal dynamics of expansion growth in roots: automatic quantification of diurnal course and temperature response by digital image sequence processing. J. Exp. Bot. 53, 689–698.

Webster, R., 2008. Soil science and geostatistics. In: Krasilnikov, P., Carré, F., Montanarella, L. (Eds.), Soil Geography and Geostatistics. Concepts and Applications. JRC Scientific and Technical Reports. Office for Official Publications of the European Communities, Luxembourg, (Chapter 1), pp. 1–11.

Woronko, B., Pochocka-Szwarc, K., 2013. Depositional environment of a fan delta in a Vistulian proglacial lake (Skaliska Basin, north-eastern Poland). Acta Palaeontol. 53: 9–21. https://doi.org/10.2478/acpa-2013-0002.