

# Geostatistical 3-dimensional integration of measurements of soil magnetic susceptibility

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**Abstract** In soil magnetometry, two types of measurements are usually performed. The first type is measurements performed on the soil surface, frequently using an MS2D sensor. The second type includes measurements of magnetic susceptibility carried out in the soil profile, usually to a depth of about 30 cm. Up to now, such measurement results were analyzed separately. However, it is possible and advantageous to integrate these two types of measurements. The goal of the study was to integrate measurements of magnetic susceptibility performed on the soil surface and in the soil profile. More specifically, the goal was to obtain 3-dimensional spatial distributions of magnetic susceptibility of the topsoil horizon. Results show that it is possible to effectively integrate measurements of magnetic susceptibility per-

formed on the soil surface and in the soil profile. Moreover, the 3-dimensional spatial distribution that is obtained shows the magnetic susceptibility of the top 20 cm of soil, which includes the soil horizons where most of the heavy metals are accumulated. The analysis of such a spatial distribution can be very helpful in delineating areas where the heightened magnetic susceptibility is a result of the influence of anthropogenic pollution from those areas where it results from lithogenic origin. It is possible to investigate where the volumes of soil with heightened magnetic susceptibility are located in the soil profile and in this way investigate which characteristic type of soil profile it is.

**Keywords** Magnetic susceptibility · Soil pollution · Heavy metals · Geostatistics · Data integration

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## Introduction

Measurements of soil magnetic susceptibility ( $\kappa$ ) have been used by many authors as a fast and inexpensive method for detecting and precise delineating areas of soil contamination by urban or industrial dust deposition (Strzyszcz and Magiera 1993; Strzyszcz et al. 1996; Kapička et al. 1997; Magiera and Strzyszcz 2000; Petrovský et al. 2000; Hanesch and Scholger 2002; Boyko et al. 2004; Desenfant et al. 2004; Chianese et al. 2005). Almost all kinds of urban and industrial dusts contain significant amounts of iron oxides, characterized by a strong magnetic suscepti-

bility. Technogenic iron oxides are known as carriers of trace elements. Consequently, dust deposited on the soil surface causes an increase of topsoil magnetic susceptibility. It was reported by many authors that soil magnetic susceptibility is strongly positively correlated with the concentration of heavy metals in the soil (Georgeaud et al. 1997; Strzyszcz and Magiera 1998; Spitieri et al. 2005).

In soil magnetometry, two types of measurements are usually performed. The first type are field measurements performed on the soil surface, frequently using an MS2D loop sensor (Strzyszcz et al. 1996; Lecoanet et al. 1999; Petrovský et al. 2000; Kapička et al. 2001; Schibler et al. 2002). The second type includes measurements of the vertical distribution of magnetic susceptibility within a topsoil profile, usually to a depth of about 30 cm (Magiera and Strzyszcz 2000; Hanesch and Scholger 2005; Fialova et al. 2006; Magiera et al. 2006). The most efficient environmental interpretation of magnetometric data requires the integration of these two types of measurements.

Distributions of magnetic susceptibility in the soil profile are often very similar to the distribution of heavy metals (Strzyszcz 1993; Strzyszcz and Magiera 1998; Hanesch and Scholger 2002; Spitieri et al. 2005). Commonly, the maximum magnetic susceptibility in the soil profile is observed at the same depth as the highest concentration of heavy metals. Additionally, using the distribution of magnetic susceptibility in the soil profile, it is possible to estimate the thickness of contaminated layer with the highest accumulation of anthropogenic magnetic particles and related heavy metals. Measurements of magnetic susceptibility in soil profiles have been used effectively to distinguish between natural (lithogenic or pedogenic) and anthropogenic contributions to measured topsoil  $\kappa$  values (Magiera et al. 2006).

The goal of this study was to integrate measurements of magnetic susceptibility performed on the soil surface and in the soil profile. Moreover, the goal was to obtain 3-dimensional spatial distributions of magnetic susceptibility of the topsoil horizons.

In addition, chemical measurements of the concentration of heavy metals were performed in order to validate the calculated 3-dimensional spatial distributions of magnetic susceptibility. The goal of this work was to investigate how useful such a 3D distribution can be in distinguishing areas where the increased  $\kappa$  value is a result of the influence of

anthropogenic pollution from those areas where it is of lithogenic origin.

## Materials and methods

### Study area

The study area was located within the Upper Silesian Industrial Area, near the town of Tamowskie Góry. All measurements were performed in the large forest park surrounding the Repty Rehabilitation Center. At present, the area of the park is closed for traffic and it is open only for pedestrians. The study area size was approximately 800–1,000 m and has irregular shape.

The majority of area was occupied by *Cambisols* developed on a thin layer of Pleistocene boulder clays sands and gravels that cover thick layers of Triassic ore-bearing dolomites rich in heavy metals such as Pb, Zn, Ag, and Cd.

Two series of magnetometric measurements were performed. The first one consisted of magnetic susceptibility measurements on the surface of the soil by a MS2D sensor. The measurements were carried out without removing the forest litter. In the point location, 10–15 individual measurements of magnetic susceptibility were performed. Then the measured values were averaged and the average was taken as the value measured at the data point. The second series included measurements of magnetic susceptibility in the soil profile performed with a SM400 device.

Later, magnetometric measurements were supplemented with one series of chemical measurements concerning the concentrations of selected heavy metals (Fe, Pb, Zn, Cd, Cu, Cr, and Ni). Chemical measurements were carried out in 18 sample points, where soil samples were collected.

### Soil magnetic measurements

Surface measurement of  $\kappa$  value was performed using a MS2D Bartington loop sensor. In total, 1,919 measurements of  $\kappa$  were carried out at the study area (Fig. 1). The measurements were done directly on the soil surface without any preparation, except for cutting of high grass or removal of twigs, at a minimum distance from the tree trunk of 1.5 m to avoid the direct influence of the surface flow effect.

**Fig. 1** Location of the study area, *small dots* sample points of surface measurements using MS2D Bartington sensor, *crosses* points of vertical cores collection using HUMAX SH 300 sampler and *squares* points of chemical measurements



Apart from the surface measurements, 27 topsoil cores ca. 20 cm depth were taken with a HUMAX SH 300 sampler equipped with plastic tubes. The cores were transported to the laboratory of Opole University and measured using MS2C Bartington sensor. Each core was measured with a vertical interval of 1 cm what gave in a result 21 values of magnetic susceptibility for each core (beginning at a depth of 0 cm and ending at a depth of 20 cm). In total, for all 27 cores, it resulted in 567  $\kappa$  values.

In the end, both surface and vertical data were jointed into one dataset of 2,486 values of soil magnetic susceptibility. In a later part of this study, these 2,486 values of soil magnetic susceptibility were referred to as sample points.

#### Soil sampling and chemical measurements

The concentration of pollutants was determined using soil samples collected at 18 points in the area of the study (Fig. 1). Samples were taken selectively from the organic horizon (O). The depth of sampling was dependent on the soil profile characteristic (morphology) in the sampling position and in most cases comprised the layer of the highest  $\kappa$  value measured in the soil cores. The total mass of individual soil sample was ca. 1,000 g. The samples were transported to the chemical laboratory

and there prepared for chemical analysis by drying out at room temperature and sieving through the 1-mm mesh. After this, the soil samples were digested by mixing concentrated nitric acid and concentrated hydrochloric acid, in a volumetric ratio of 1:3 (*aqua regia*). The concentrations of selected heavy metals (Fe, Pb, Zn, Cd, Cu, Cr, and Ni) were determined by atomic absorption spectrophotometry.

#### Geostatistical methods

Geostatistics offers many methods for evaluating the autocorrelation of spatial data and the most common is the semivariance function. The experimental semivariance for a vector of separation  $\mathbf{h}$  is calculated as one half of the average squared difference between the pair of values measured at locations separated by this vector. Semivariance values are then plotted against the separation distance between pairs of sample points and the plot is commonly referred as to a variogram (Isaaks and Srivastava 1998; McBratney and Webster 1986). The following formula was used for the semivariance calculations:

$$\gamma(\mathbf{h}) = \frac{1}{2N} \sum_{i=1}^N [Z(\mathbf{x}_i) - Z(\mathbf{x}_i + \mathbf{h})]^2$$

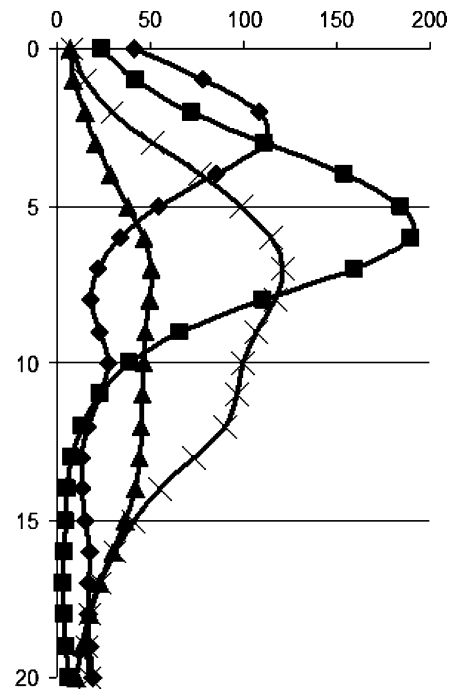
where,  $\mathbf{x}_i$  is a location,  $\mathbf{h}$  is a lag vector,  $Z(\mathbf{x}_i)$  is the measured value at location  $\mathbf{x}_i$ , and  $N$  is the number of pairs spaced by the  $\mathbf{h}$  vector.

The result of measurements performed with the MS2D and SM-400 sensors is a dataset of volume magnetic susceptibility located in 3-dimensional space. In this connection, it was possible to calculate the 3-dimensional spatial distributions using ordinary kriging. Ordinary kriging is the most effective linear estimator since it assumes that the average value of the estimation error equals zero, and the variance of estimation error is minimized (Goovaerts 1997). The values are estimated at the unsampled location  $Z_0(\mathbf{x}_0)$  using values from  $n$  neighboring measurement points  $Z_i(\mathbf{x})$  weighted by weights  $\lambda_i$  that are determined using a semivariance function and are chosen for each sample point within search radius. The search radius was determined using the range of a variogram model.

$$Z_0(\mathbf{x}_0) = \sum_{i=1}^n \lambda_i \cdot Z_i(\mathbf{x})$$

## Results and discussion

The analysis of the vertical distributions of  $\kappa$  value in soil profiles showed that in most profiles it reached a maximum at a depth of 3–5 cm (Fig. 2, Table 1), which is connected with the presence of the organic horizon in the topsoil. This horizon is usually a collector of atmospheric pollution deposited on the soil surface including technogenic magnetic particles and related heavy metals. Such an “anthropogenic peak” of  $\kappa$  value is characteristic of areas with strong anthropogenic pressure (Magiera and Strzyszc 2000; Henesch and Scholger 2002; Magiera et al. 2006; Blaha et al. 2008). Statistically, the layer of maximum magnetic enhancement was at a depth of 5 cm, whereas at a depth of 16 cm, the  $\kappa$  value reaches a stable level, considered as the soil background value (Table 1). An absolute value of this magnetic enhancement depends on the level of pollution, soil type, and soil profile development. In the studied area, the maximum  $\kappa$  values were between 50 and  $200 \times 10^{-5}$  International System of Units (SI) magnetic units. In the deeper parts of the soil profile, the magnetic susceptibility was constantly decreasing and in some of the profile, reached an almost constant value. Such a vertical distribution of  $\kappa$  value was described by Magiera et al. (2006) as type A1. The



**Fig. 2** Exemplary vertical distributions of magnetic susceptibility in soil profile measured with MS2C Bartington core sensor

A1 type is characterized by strong magnetic enhancement at a depth of about 3 cm and then gradual decrease with the depth. Second noticeable enhancement is usually observed at about 20 cm, which is the result of paramagnetic iron oxides and hydroxides accumulated in the illuvial horizon.

In five soil cores, the vertical distribution of  $\kappa$  value in the soil profile was in the form of a wide peak within the uppermost 10 cm (line with crosses in Fig. 2). Such a  $\kappa$  distribution is described by Magiera et al. (2006) as type A3 and is commonly observed under deciduous forest stands. The A3 type is characterized by a wide peak within the uppermost 10 cm, and then values of magnetic susceptibility are stabilized at a low level. Second enhancement is usually observed at about 20 cm. The A3 type is usually observed in soil located in a deciduous forest.

All observed soil profiles exhibit an anthropogenic pattern of  $\kappa$  distribution along the soil profile. The highest  $\kappa$  values are observed at depth between 2 and 7 cm below surface (Fig. 3). Lithogenic influence is low because of the geological background. The soils are mostly *Cambisols* developed on a thin layer of Pleistocene boulder clay sands and gravels that cover

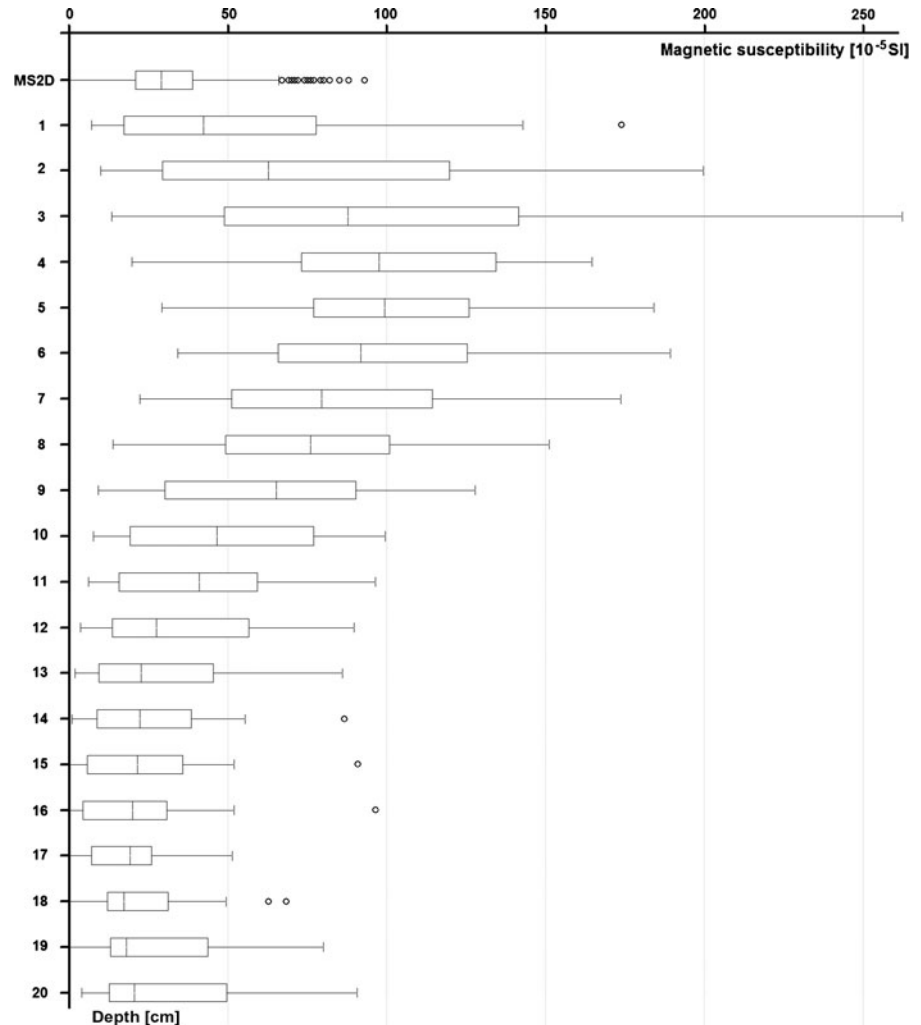
**Table 1** Descriptive statistics of depths with maximum  $\kappa$  value, depth of stabilization of  $\kappa$  value consider as a soil background value

	Depth where magnetic susceptibility	
	Reaches maximum	Stabilizes
Average (cm)	5.1	16.7
Standard error (cm)	0.4	0.5
Median (cm)	5.0	16.0
Standard deviation (cm)	2.0	2.7
Variance (cm <sup>2</sup> )	4.2	7.4
Kurtosis (–)	–0.43	–0.75
Skewness (–)	0.28	0.44
Range (cm)	8.0	10.0
Minimum (cm)	2.0	13.0
Maximum (cm)	10.0	23.0

thick layers of Triassic ore-bearing dolomites rich in heavy metals such as Pb, Zn, Ag, and Cd. The clay minerals containing Fe in their structure, that are present in the C horizon, are sometimes responsible for a slight enhancement of  $\kappa$  value on the bottommost part of the profile due to their paramagnetic properties. In some profiles where the C horizon is built of dolomite debris, which has diamagnetic properties, the lower part of the studied profiles have  $\kappa$  values of  $<10 \times 10^{-5}$  SI magnetic units. In some cases even, negative  $\kappa$  values typical of diamagnetic substances such as pure quartz sand or calcium carbonate were measured at a depth below 15 cm.

The analysis of correlations between the magnetic susceptibility measured on the soil surface and those measured in the soil profile was performed using

**Fig. 3** Box and whisker plots of  $\kappa$  values measured on the soil surface with MS2D loop Bartington sensor and at different depths measured with MS2C Bartington core sensor



classic statistics. Pearson's correlation coefficients are listed in Table 2.

The magnetic susceptibility measured with an MS2C Bartington sensor in soil cores at depths of 1, 2, and 3 cm was practically uncorrelated with the magnetic susceptibility measured with an MS2D Bartington sensor on the soil surface (Table 2). This observation can be explained by the fact that the first 3 cm of soil were occupied by the O1 subhorizon. This subhorizon is composed of organic matter which reveals strong diamagnetic properties. This layer does not accumulate magnetic particles and other chemical contaminants. The rapid increase of correlation was observed for magnetic susceptibility measured at a depth of 4 cm. The maximum value of Pearson correlation coefficient was observed at a depth of 5 cm where the  $\kappa$  value is usually the highest. Magnetic susceptibility measured deeper in the soil profile, from 6 to 8 cm, was also strongly correlated with those measured on the soil surface. However, the strength of correlation decreased with depth. For magnetic susceptibility at a depth of 9 cm, correlations with those measured with the MS2D sensor were statistically insignificant. As the penetration depth of this sensor is about 10 cm, almost 50% of the total signal is detected from a depth of 1.5 cm and 90% of the total signal from a depth of 6 cm (Lecoanet et al. 1999). So the O1 subhorizon creates an isolation layer and may possibly lower the  $\kappa$  values measured on the soil surface; therefore, it is recommended to remove forest litter (O1 subhorizon) before the surface measurement. Consequently, the hypothetical advantage of forest litter removal is that the MS2D Bartington sensor will be able to gather a

magnetic signal more strongly correlated with the peak  $\kappa$  in the soil profile (Zawadzki et al. 2009). The penetration range of the MS2D sensor was too short to measure the magnetic susceptibility at deeper soil horizons.

In order to calculate the 3-dimensional spatial distribution, it was necessary to investigate the spatial correlation of soil magnetic susceptibility. Firstly, spatial correlations were investigated using 2,486 values of magnetic susceptibility based on the joint datasets of MS2D and MS2C measurements. The experimental variogram was calculated using 15 classes of 45 m long lag (Fig. 4).

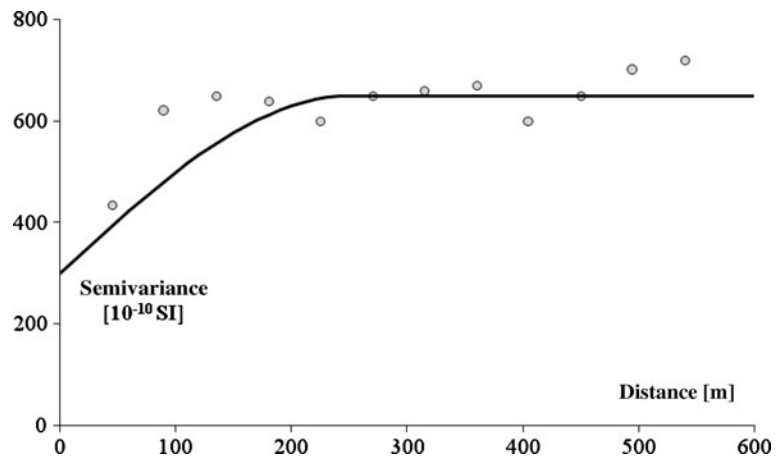
The experimental variogram was modeled based on the nugget effect and spherical model. The nugget effect, equal  $3 \times 10^{-8}$  SI magnetic units, was rather high in comparison with the sill of  $6.5 \times 10^{-8}$  SI magnetic units. However, it was possible to observe well-defined spatial continuity and a range of correlation equal to 300 m. The analyzed variogram was calculated using all values of magnetic susceptibility, but there was a significant difference between the dimensions of study area in the horizontal and vertical surfaces. Consequently, the observed range of 300 m reflected the horizontal spatial correlations of magnetic susceptibility, mostly those measured on the soil surface. In this connection, it was necessary to investigate the spatial correlations of magnetic susceptibility measured at different depths in the soil profile. For this reason, 21 variograms were calculated, each one for magnetic susceptibility measured at every 1 cm interval from the surface (0 cm) down to 20 cm. Particular variograms were calculated using lag distance of 45 m and the parameters of variogram models were fitted using least square method (Table 3).

The spatial correlations of magnetic susceptibility measured at depths of 0 and 1 cm were modeled with a Gaussian model. This also means that the magnetic susceptibility measured close to the soil surface was characterized by the small changes in spatial correlations for short distances between sample points. This uppermost soil layer was occupied by the O1 subhorizon which mostly consists of fresh organic matter and reveals strong diamagnetic properties. The  $\kappa$  values measured here were practically unrelated to anthropogenic pollution and, consequently, spatial correlations were mostly determined by natural soil litter factors including tree stand and low vegetation (Zawadzki et al. 2010).

**Table 2** Pearson correlation coefficients between magnetic susceptibility measured on the soil surface with MS2D loop sensor and magnetic susceptibility measured at different depths in the soil profile with MS2C core sensor

Depth (cm)	On the soil surface
1	−0.01
2	0.01
3	−0.02
4	0.28
5	0.44
6	0.43
7	0.33
8	0.17
9	0.00
10	−0.10

**Fig. 4** Experimental variogram and its model for  $\kappa$  value measured on the soil surface with MS2D Bartington loop sensor and  $\kappa$  value measured in vertical soil profile with MS2C Bartington core sensor



In the case of  $\kappa$  values measured deeper in the soil profile, spatial variograms were modeled using the pure nugget effect or spherical model (Table 3). For magnetic susceptibility measured at depths from 2 to 8 cm, the changes in spatial correlation for short distances between samples were higher in comparison with magnetic susceptibility measured at depths of 0 and 1 cm. At depths from 2 to 8 cm in soil profile including mostly the lower subhorizons of organic horizon (Of and Oh) and Ah horizons, the majority of technogenic magnetic particles are accumulated, therefore these caused a higher spatial variability of the  $\kappa$  value.

Only in the case of magnetic susceptibility measured at depths from 0 to 8 cm was it possible to determine the range of spatial correlation. The range of spatial correlations increased for the magnetic susceptibility measured at increasing depths in soil profile. For the magnetic susceptibility measured at a depth of 0 cm, the range of spatial correlations was equal to about 265 m, and the longest range of spatial correlations, equal to 485 m, was observed for magnetic susceptibility measured at a depth of 6 cm. Such observations show that the spatial variability determined by anthropogenic pollution increased with the depth in the soil profile. At depths ranging from 6 to 8 cm, the range of spatial correlations was still considerable and equal to 400 m, in spite of the significant decrease in the values of magnetic susceptibility (Table 3, Fig. 5).

The magnetic susceptibility measured deeper than 10 cm in the soil profile was characterized by poor spatial correlations. Variograms of magnetic susceptibility measured at these depths were modeled using

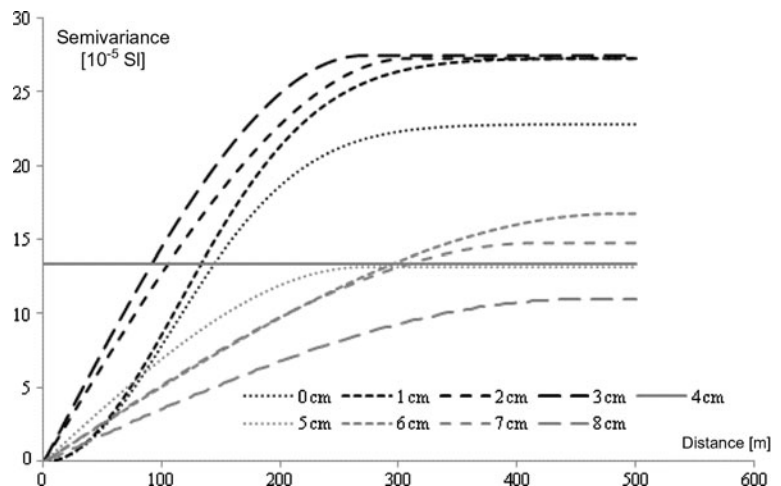
only the pure nugget effect. The values of the nugget effect decreased for variograms calculated at increasing depths. This observation can be explained by the

**Table 3** Parameters of variogram models of  $\kappa$  value measured at depths from 0 to 20 cm

Depth (cm)	Parameters of variogram model		
	Nugget effect ( $10^{-10}$ SI)	Range (m)	Sill ( $10^{-10}$ SI)
0	–	265 (G)	760
1	–	280 (G)	2,280
2	–	308 (S)	2,730
3	–	270 (S)	2,743
4	1,339	–	–
5	–	270 (S)	1,320
6	–	485 (S)	1,677
7	–	417 (S)	1,477
8	–	453 (S)	1,100
9	1,055	–	–
10	764	–	–
11	568	–	–
12	512	–	–
13	447	–	–
14	392	–	–
15	393	–	–
16	442	–	–
17	474	–	–
18	471	–	–
19	491	–	–
20	404	–	–

G Gaussian model, S spherical mode

**Fig. 5** Variograms of  $\kappa$  value measured at the depths from 0 to 8 cm in soil profile



fact that values of magnetic susceptibility reduced with depth and also the variance of the  $\kappa$  value decreased considerably. Only in the case of variogram calculated at depths ranging from 16 to 19 cm was an increase in the nugget effect value observed. This could be caused by the increasing  $\kappa$  values in some profiles as a result of the accumulation of paramagnetic iron minerals in the C horizon in profiles developed on Pleistocene boulder clays

Along with the increase of the depth in soil profile where the  $\kappa$  value was measured, the sill of proper variograms increased reaching a maximum value at a depth of 3 cm. Statistically, in the soils studied, a depth of 3 cm was the boundary between OI and Of subhorizons. However, the thickness of the litter (OI) is variable in the study area. This means that at some profiles with thicker OI subhorizon, the  $\kappa$  value was determined by diamagnetic organic matter, whereas in other profiles at the same depth there was fermentation or humic subhorizons (Of, Oh) where the magnetic signal was determined by technogenic ferromagnetic minerals accumulated there. This heterogeneity could be a cause of the heightened variance of magnetic susceptibility and consequently a cause of increased sill values.

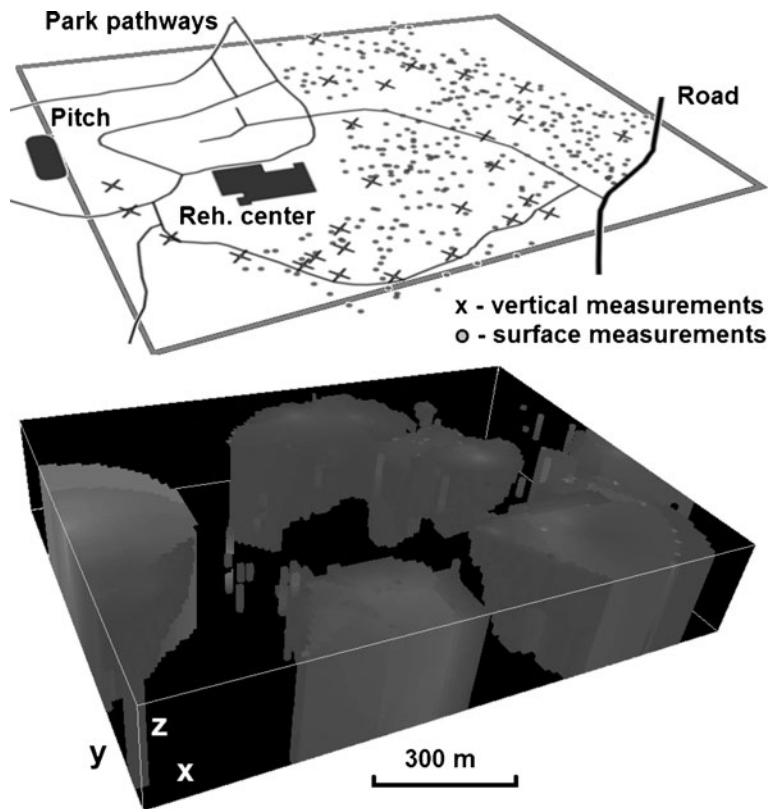
The calculated 3-dimensional spatial distribution of soil magnetic susceptibility covered the part of the soil profile from the surface to a depth of 15 cm. Figure 6 presents the volumes of soil where the magnetic susceptibility exceeded values of  $50 \times 10^{-5}$  magnetic units. According to previous studies (Magiera 2004), such a value can be used as an indicator of potential soil pollution with heavy metals.

In the majority of the study area, especially in the vicinity of a public road and near the building of the Rehabilitation Center, the  $\kappa$  values exceeded  $50 \times 10^{-5}$  SI magnetic units. In some profiles, the increased  $\kappa$  values were observed up to 10 cm below the surface whereas in others even up to 15 cm. The maximum  $\kappa$  value was observed within the layer 3–5 cm below the surface. In this subhorizon, the majority of anthropogenic contaminants including technogenic ferromagnetic particles and related heavy metals were accumulated. Such observations suggest that the increased values of magnetic susceptibility were caused by anthropogenic pollution.

In the northern part of the study area, heightened  $\kappa$  values exceeding  $50 \times 10^{-5}$  SI magnetic units were observed through the entire soil profile. However, in other parts of the studied area, the soil volumes where magnetic susceptibility exceeded  $50 \times 10^{-5}$  magnetic units were mostly located in the upper 10 cm of the soil profile. At depths from 10 to 20 cm,  $\kappa$  values were lower. The decreasing tendency towards the deeper horizons means that the magnetic particles were accumulated in the topsoil as a result of anthropogenic dust fall.

Results obtained on the basis of soil magnetometry were verified using chemical measurements. In the study area, 18 reference samples for chemical analysis were collected from the topsoil. Seven elements (Fe, Pb, Zn, Cd, Cu, Cr, and Ni) were detected in the samples (Table 4). The spatial distributions of some measured heavy metals were calculated from a relatively small number of chemical measurements, so the inverse distance weighting

**Fig. 6** The 3-dimensional spatial distribution of those volumes of soil where magnetic susceptibility exceeded value of  $50 \times 10^{-5}$  SI. The distances along the Z axis—the depth in the soil profile where scaled by exaggerated factor in order to make the figure more readable



method was used for the compilation of maps presented in Fig. 7.

The results of the chemical measurements showed that the concentrations of particular heavy metals in the soil were high, especially in the case of Pb, which in all samples was above national threshold values (100 mg/kg). Especially in the northeastern part of the studied area, the concentration was six to seven times

higher than the threshold. In the case of zinc, the threshold values were exceeded in seven samples and in the case of cadmium in five samples. The Pearson correlation coefficients between  $\kappa$  value and Pb, Zn, and Cd are very low (between 0.17 and 0.25), which means that most of these heavy metals are related to geogenic sources. The presence of ore-bearing dolomites in the geological background increases a local geochemical

**Table 4** Descriptive statistics of heavy metal concentration in soil and Pearson correlation coefficients between magnetic susceptibility and heavy metals concentration in soil

	Average	Median	Minimum	Maximum	Quartile		Standard deviation	Pearson correlation coefficient
					25%	75%		
(mg kg <sup>-1</sup> )								(-)
Cd	3.00	2.52	0.77	7.14	1.72	4.38	1.80	0.16
Cr	9.32	8.86	2.94	21.58	5.65	12.06	5.39	0.36
Cu	39.10	20.68	9.11	331.29	14.76	28.91	73.77	0.03
Fe	11,255.44	9,974.50	5,438.00	24,618.00	8,725.75	12,795.25	4,786.70	0.35
Ni	6.31	6.48	0.05	12.06	4.43	7.82	3.25	0.41
Pb	339.00	265.76	114.42	706.65	203.13	479.36	189.01	0.44
Zn	350.96	265.52	90.21	1,807.70	211.41	326.99	375.19	0.25

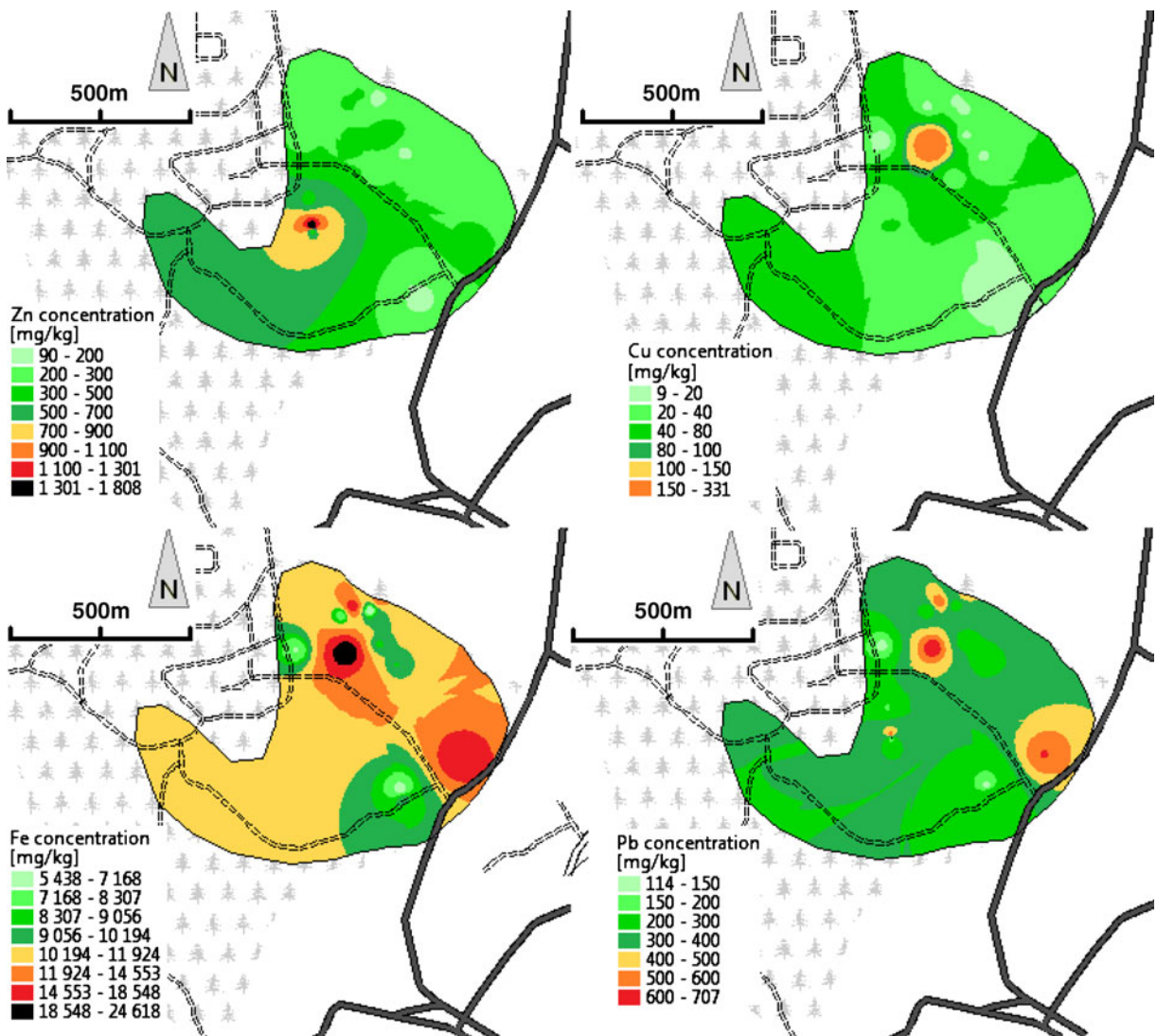


Fig. 7 Spatial distribution of Zn, Cu, Fe, and Pb concentration in soil

background that is not related to technogenic magnetic particles. Only the correlation between Cu content and magnetic susceptibility is at a level over 0.50, which suggests that only this metal present in the topsoil is of anthropogenic origin; however, its concentration is mostly below the threshold value of 150 mg/kg and this value was exceeded only at one sample location. Also, correlation between total Fe content and  $\kappa$  values measured on the surface is low at a level of 0.23. This could be connected with the presence of iron sulfides in ore-bearing dolomites and their debris which comprised in some profiles the C horizon. The average concentration of Fe in the soil was equal to 11,255 mg/kg (Table 4) and was a few times higher

than the average concentration of Fe in the soils of Poland (Kabata-Pendias and Pendias 2000). Only this part of iron that has a technogenic origin resulting from industrial and urban dust fall is in ferromagnetic forms that are highly correlated with magnetic susceptibility. Most of the total iron extracted here is in paramagnetic sulfide forms.

## Conclusions

Results showed that it is possible to effectively integrate measurements of magnetic susceptibility performed on the soil surface and in the soil profile.

Moreover, the 3-dimensional spatial distribution obtained in this way shows the magnetic susceptibility of the top 20 cm of soil, which includes those soil horizons where most of the heavy metals are accumulated. The analysis of such a spatial distribution can be very helpful in distinguishing areas where the heightened magnetic susceptibility is a result of the influence of anthropogenic pollution from those areas where it is of lithogenic origin. It is possible to investigate where the volumes of soil with heightened magnetic susceptibility are located in the soil profile and in this way investigate which characteristic type of soil profile it is.

As a possible extension of the analysis, the authors consider the use of cumulative semivariogram as well as point cumulative semivariogram in order to overcome some disadvantages of classical semivariogram described detailed by Şen (1989, 1998). It would give a better possibility to study magnetic susceptibility in larger scale around any desired site by considering the remaining measurements.

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