Environ Monit Assess (2007) 125:19–28
DOI 10.1007/s10661-006-9235-4

ORIGINAL ARTICLE

Using of high-resolution topsoil magnetic screening for assessment of dust deposition: comparison of forest and arable soil datasets

T. Magiera · J. Zawadzki

Received: 6 July 2005 / Accepted: 1 March 2006 / Published online: 23 August 2006

Abstract Magnetic susceptibility (κ) is an easily detectable geophysical parameter that can be used as a proxy or semi-quantitative tracer of atmospheric industrial and urban dusts deposited in topsoil. An enhanced κ value of topsoil is in many cases also associated with high concentrations of soil pollutants (mostly heavy metals). High-resolution magnetic screening of topsoil in areas of high pollution influx is a useful tool for detection of pollution "hot spots". General and regional screening maps with a grid density of 10 or 5 km have been performed on the basis of forest topsoil measurement only. The purpose of this study was to perform high-resolution magnetic screening with different grid densities in both forested and agricultural areas (arable land). Our large study area (ca. 200 km^2) was located in a relatively more polluted region of the central part of Upper Silesia, and a second (small) one (ca. 100 m^2) was located in the western part of Upper Silesia, with considerably lower influx of pollution. In the framework of this study, we applied a statistical comparison of data obtained in forested areas and on arable land. The arable soil showed statistically significantly lower κ values, the result of "physical dilution" of the arable layer caused by annual ploughing. Thus arable soils must be avoided during high-resolution field measurement. From semivariograms, it was clear that the spatial correlations in forest topsoil are much stronger than in arable soil, which suggests that a denser measurement grid is required in forested areas.

Keywords Basic statistic · Magnetic susceptibility · Soil pollution · Topsoil · Semivariances

1 Introduction

Magnetic susceptibility (κ) is a measure of the degree to which a substance can be magnetized when subjected to a magnetic field (Thompson and Oldfield, 1986). In the case of soil, the κ value is ultimately related to the concentration and composition (size, shape and mineralogy) of magnetic material contained within the sample. Magnetic susceptibility measurements are a non-destructive and cost-effective method of determining the presence of iron-bearing minerals within the soil. The magnetic susceptibility of topsoil is in most cases related to the concentration of iron oxides of anthropogenic origin, which constitute a significant part of atmospheric industrial and urban dusts and aerosols. Moreover, these iron oxides are known to serve as carriers of various pollutants such as heavy metals (Hullet *et al.*, 1980; Hansen *et al.*, 1981). Thus, magnetic screening of soil provides information over and above that provided by conventional contamination detection

T. Magiera (✉)
Institute of Environmental Engineering PAS, ul. Sklodowskiej-Curie 34, 41-819 Zabrze, Poland

J. Zawadzki
Warsaw University of Technology, 00-661 Warszawa, ul. Nowowiejska 20, Poland
e-mail: magiera@ipis.zabrze.pl

and monitoring methods, and can reduce analytical costs through a more effective sampling strategy (Strzyszcz, 1993; Strzyszcz *et al.*, 1994; Heller *et al.*, 1998; Kapika *et al.*, 1999).

Strzyszcz (1993; 1995), Strzyszcz *et al.* (1996) and Heller *et al.* (1998) studied the magnetic susceptibility of soils in different regions of Poland and defined specific areas characterized by enhanced magnetic susceptibility values (see also the references given therein). Increased magnetic susceptibility correlates well with high iron oxide emissions produced by power plants, by the steel and cement industries, and associated with major urban areas, particularly in the Silesian province. The central part of this area, covering some 1,500 km^2, is host to probably the greatest density of industrial pollution sources in Europe. Magnetic susceptibility in forest soils of the Silesian province, measured in different soil horizons (litter layer, fermentation and humic), could be closely linked to sources of pollution nearby (Strzyszcz *et al.*, 1996).

The magnetic study of topsoil was usually based on forested areas. In contrast to arable soil, forest soil profiles preserve their natural structure. In general forest soils have well-developed uppermost soil horizons (O, Ah), which serve as a filter in which industrial and urban pollutants (including heavy metals and anthropogenic magnetic particles) are concentrated. In vertical forest soil profiles the highest κ value is usually observed just below the litter (Ol), in fermentation and humic subhorizons (Of, Oh) (Heller *et al.*, 1998).

On-site mapping of soil magnetic susceptibility was used as a proxy, simple, fast and cost effective method for measurement of the spatial distribution of pollution in the framework of the MAGPROX Project (Magiera *et al.*, 2003). In this project, the field method of topsoil magnetic screening was applied in combination with use of the Geographic Positioning System (GPS) for automatic and precise mapping of susceptibility distribution, in order to determine the magnetic "hot spots" (Schibler *et al.*, 2002). The whole study area was ca. 200, 000 km^2. A general screening map of magnetic susceptibility was compiled with an average grid density of 10 km. The study was performed in forested areas. The measuring sites were located within 2 km from the grid node, preferentially in old forests with stands of coniferous trees. The measurement was done at least 50 m from the forest margin, from any road and from any potential sources of pollution. On such a large scale, some local magnetic "hot spots" were probably omitted. Identified 'hot spots' of topsoil magnetic susceptibility can be considered to be potentially contaminated areas, and must be investigated more precisely to outline the exact shape and range of the anomaly. In the second stage of the study, high-resolution mapping with a measurement grid of 1×1 km was used. However, in such a dense grid it is impossible to locate the measurement sites only in forested areas. The aim of this study was to make a statistical comparison between κ measurements obtained in forested areas and those obtained on arable land field located close by, the two areas being under equal influence from industrial and urban emission and being subject to the same degree of dust deposition.

2 Description of areas, methods, and materials studied

The study area was located in Upper Silesia (in southern Poland). Two areas of different scale were selected for this study. The large area (ca. 200 km^2) was located in the southern edge of the Upper Silesian Industrial Region, which is the largest "magnetic hot spot" in Central Europe (Magiera *et al.*, 2002, 2003). The area was selected on the basis of results obtained during the earlier regional study in the grid of 5×5 km (Magiera *et al.*, 2003). The measurement sites were located in the administrative territory of 5 Silesian cities: Mikolow, Katowice, Tychy, Laziska Gorne and Orzesze (Fig. 1). The area has different levels of pollution and consists of industrial areas, urban areas, rural areas and forest.

The small area was located 30 km north-west of the western edge of the large area, in Rudziniec Forestry where the total dust deposition level and topsoil magnetic susceptibility are considerably lower. There were 2 separate areas of 50 m^2 (forested area and arable land) located close to each other (300 m apart), and covered by a high-density (20×20 m) measurement grid.

The measurements for the large area were performed in a 1-km grid directly in the field, on the soil surface, using the Bartington MS2 (Magnetic Susceptibility System) with an MS2D loop sensor that was fully integrated with a GPS external sensor (Trimble Pathfinder Pro XRS). Thus, each MS2 measurement value is associated with GPS coordinates, and accuracy is greater than 10 m. Ten to fifty measurements were done in 1 grid point (a square 2×2 m) The number of single measurement was dependent of variability of κ value

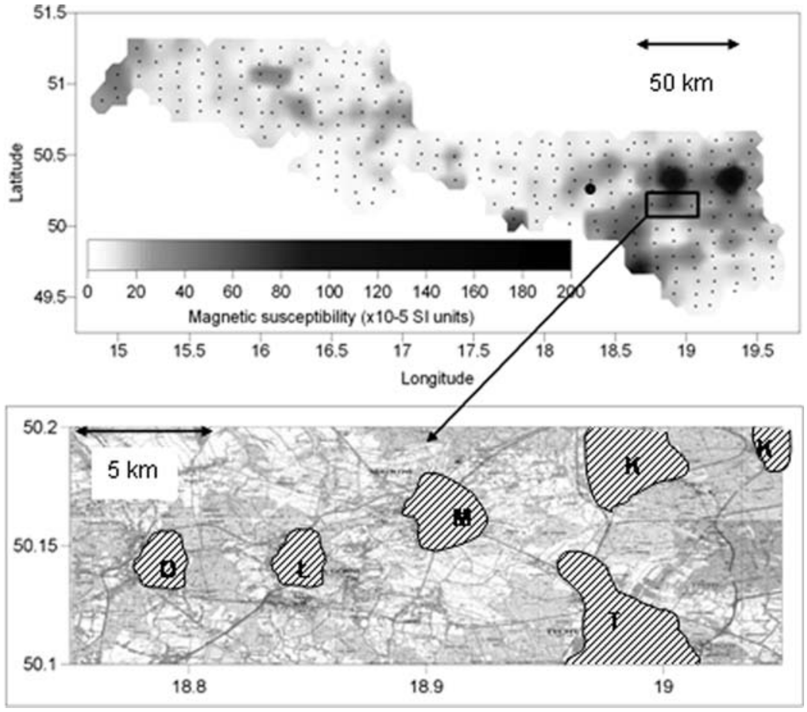

Fig. 1 Localization of study areas on the map of south-western Poland. Rectangle shows large study area and black circle shows small study area. The lower part of the figure is a topographic map of the large study area with main urban areas. The following urban areas are marked on the map: O – Orzesze, L – Laziska, M – Mikolow, T – Tychy, K – Katowice.

in grid point area. Slopes (over 5%), rock outcrops and areas of visible surface erosion were avoided as far as possible. In forest, the minimum distance from the tree trunk was 1 m. Measurement was done without any surface preparation, except for cutting of high grass or removal of twigs.

The same measurement methodology was used in the small area however, the measurement grid was considerably more dense (ca. 20×20 m^2). Due to the higher variability of κ values in forested areas as, many as 104 single measurements were performed in the forest of small area, whereas only 28 grid points were located on arable field. In the large area, 93 measurement sites were located in forested areas and 58 on arable land.

To perform the comparison between κ measurements obtained in forested areas and on arable soil the analysis of basic statistical parameters (means, medians, standard deviations, range, skewness and kurtosis) were used together with standardised semivariance as a geostatistical measure of spatial continuity (Webster and Olivier, 1990).

Semivariance was expressed in the graphical form of semivariogram, where semivariance (γ) is half the expected squared difference between values of susceptibility at a distance of separation (lag, h) calculated in both distance and direction (Isaaks and Srivastava, 1989; Webster and Olivier, 2001). The experimental semivariance γ ($\boldsymbol{h}$) is calculated as:

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

where $\boldsymbol{h}$ is the lag (in pixels) over which γ (semivariance) is measured, N is the number of observations used in the estimate of $\gamma(\boldsymbol{h})$, and k is the value of the variable of interest at spatial position x_i. The value $k(x_i+\boldsymbol{h})$ is the susceptibility value at lag $\boldsymbol{h}$ from $\boldsymbol{x}$.

Semivariance is roughly summarized by three characteristics:

- sill – the plateau that the semivariance reaches. The sill is the amount of variation explained by the spatial structure
- range of the influence (correlation). The distance at which the semivariance reaches the sill
- nugget effect – the vertical discontinuity. The nugget effect is a combination of sampling error and short-scale variations that occur at a scale smaller than the closest sample spacing. The sum of the nugget effect and sill is equal to the variance of the sample.

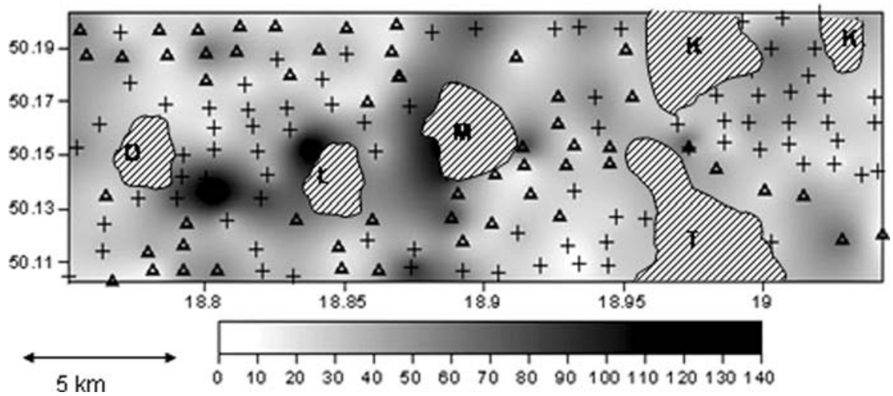

Fig. 2 Detailed map of topsoil magnetic susceptibility distribution ($\kappa \times 10^{-5}$ SI units) on large study area, based on all data obtained in a measurement network of 1 × 1 km. Urban areas are as in Fig. 1.

The empirical standardized semivariograms (which are referred, to hereafter briefly to as semivariograms) were calculated from the susceptibility measurements.

3 Results and analyses

All data obtained in the large study area were compiled on the map of κ distribution (Fig. 2). The measured values of κ were in the broad range between 0 and 150 × 10^{-5} SI units. The lowest values were found in forested and agricultural areas between Tychy and Mikolow, and in agricultural areas north of Orzesze and Laziska. Three large "hot spots" are located in western and central part of the study area, close to Laziska Gorne and Mikolow. The "hot spot" areas are associated with industrial sources of pollution – the Laziska iron works and power plant, which are located between Laziska Gorne and Orzesze, as well as the local industry and urban areas of Mikolow. The results look slightly different if one compares two separate maps compiled for forested areas and arable soil (Fig. 3). The magnetic "hot spots" are visible only on the map compiled on the basis of forest soil data. This raises the question of whether the measured κ value of topsoil is only the result of accumulation of magnetic particles or if the

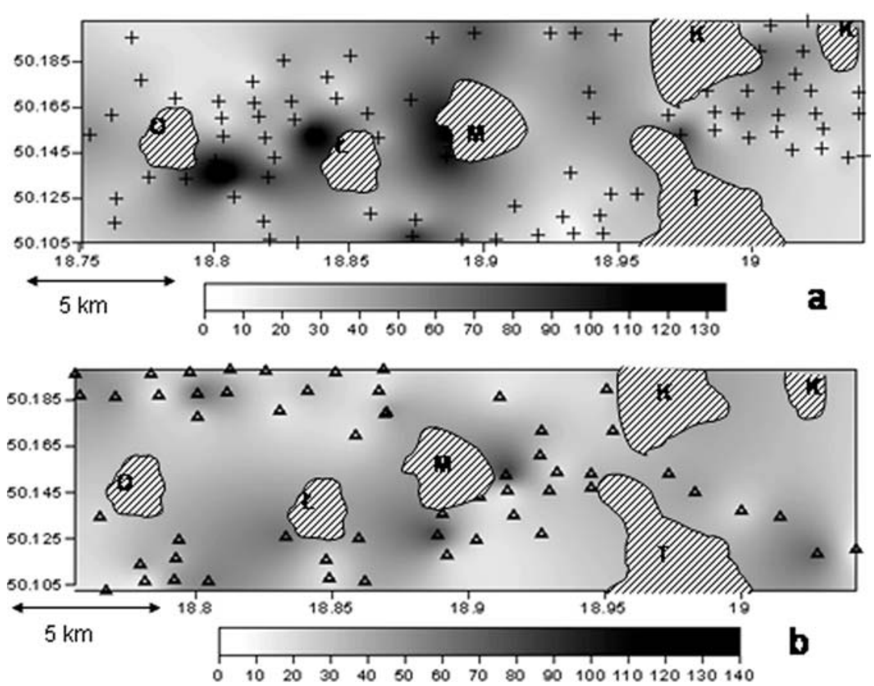

Fig. 3 Detail maps of topsoil magnetic susceptibility distribution ($\kappa \times 10^{-5}$ SI units) based on a) –measurement only in forested areas; b) –measurement only on arable land. are as given in Fig. 1.

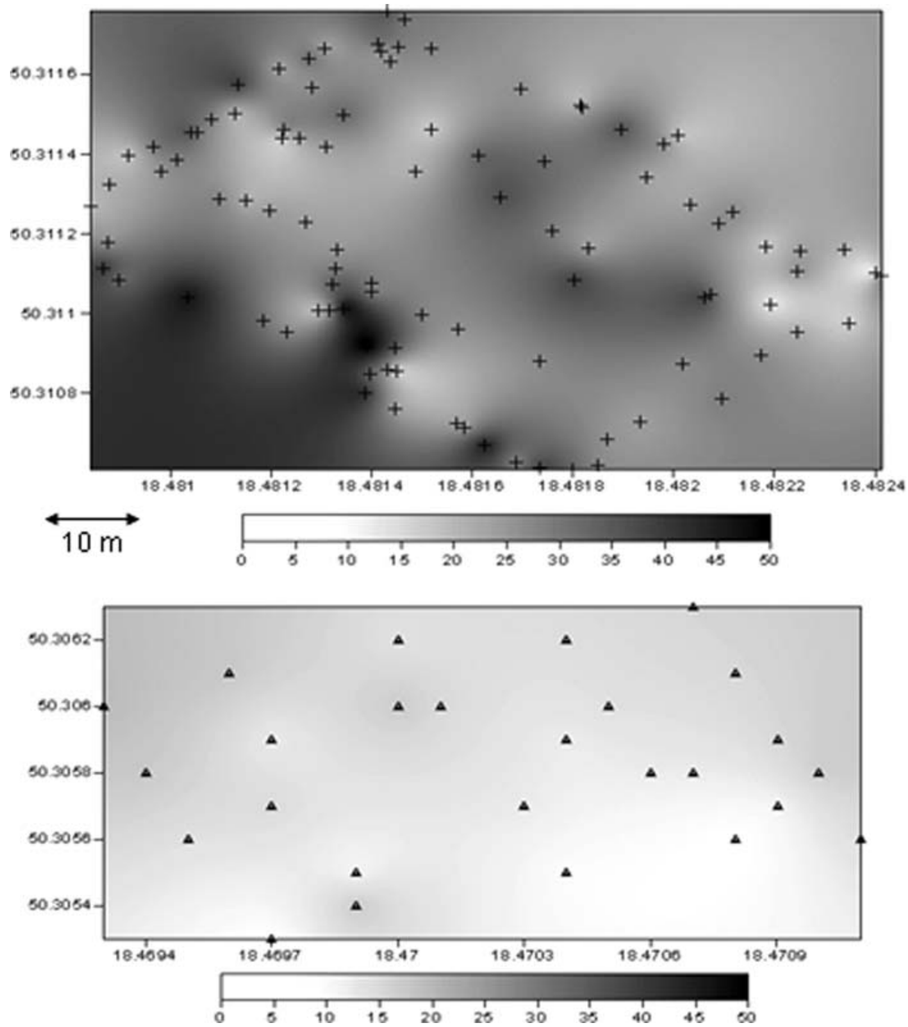

Fig. 4 Detailed maps of topsoil magnetic susceptibility distribution ($\kappa \times 10^{-5}$ SI units) on the small study area based on: a) measurement in forested area, b) measurement on arable land.

different land use influences the results obtained and also to what extend the forest and arable data are comparable.

The forested and agriculture areas investigated were rather large and isolated from each other, which raises some doubt as to whether there were the same conditions of deposition over whole area under study.

For this reason, the similar measurements of topsoil κ value were also performed on additional small areas, where the pollution influx, soil type and geological background was the same.

In the vicinity of Rudziniec, where the small study area was located, the forest topsoil κ values observed were in the range of $5 - 50 \times 10^{-5}$ SI units. The spatial variability in this area is considerably high, especially if we compare the values for arable land (Fig. 4). On arable land the κ values measured were very stable, in the range $15{-}20 \times 10^{-5}$ SI units.

When we compared statistical parameters, considerable differences were observed between forested areas and arable ones. In the case of forested areas, the mean and median values were considerably higher, irrespective of the size of study area (Table 1). In large area, the standard deviations were much higher (28.3 SI units in forest and 18.5 SI units in arable land) than in small areas (7.7 SI units and 1.6 SI units, respectively). This observation can be explained by the sizes of the areas investigated, and the higher variability of dust deposition conditions in larger areas. The ranges and standard deviations of data in forest areas were

Table 1 The basic statistical parameters for distribution of κ value in forested areas and on arable fields

	Forested large area	Arable large area	Forested small area	Arable small area
Count	93	58	104	41
Mean	42.5	33.5	27.7	17.7
Median	35.0	31.3	27.0	18.0
Standard deviation	28.3	18.5	7.7	1.6
Minimum	6.0	2.6	6.0	15.0
Maximum	147.9	91.7	52.0	20.0
Skewness	1.7	1.0	0.6	−0.1
Kurtosis	3.0	1.2	0.9	−1.1

considerably higher than on arable land both for small and large areas (Fig. 5a, b).

The positive skewness values indicate significant right-skewed distributions of forest data in large areas (Table 1, Fig. 5a). The skewness for arable land in large areas and forest data on small areas are considerably lower, but still positive. Only negative skewness values were observed for arable land in small area (Fig. 5b). As the right-skewed data distributions are commonly observed for soil pollution (Goovaerts, 1997), the arable soil in the small area, where the pollution influx is rather low, is dominated by natural magnetic features.

The t-test for two populations with unknown and unequal variances (Kanji, 1993) was used to investigate the significance of the difference between the means of susceptibility measurements in forest and arable land both for large and small areas investigated. In both cases, it was found that there is a statistically significant difference (at the 5% of level) between the means of measurements made in forest and arable land. These results suggest that land use has the important influence on the surface κ value measured.

Comparison of means (by t -test) showed that in the case of large areas, the 95.0% confidence intervals for the means of forests measurements were between 36.7 and 48.3 $\times$ 10^{-5} SI units, and the 95.0% confidence interval for means of arable soil measurements were between 28.6 and 38.3 $\times 10^{-5}$ SI units. For small areas the same confidence intervals were between 26.2 and 29.2 $\times$ 10^{-5} SI units and between 17.2 and 18.2 $\times$ 10^{-5} SI units for forests and arable soil, respectively.

From the above results, one can conclude that the arable field has a relatively lower and more stable susceptibility signal than that measured for forest, irrespective of the size of the area investigated and grid density.

The empirical standardized semivariances were also calculated for all four regions (Fig. 6a and b, 7a and b). As can be seen clearly from these figures, the semivariances obtained depend on both the measurement scale and the type of land use. They also seem to be very sensitive to the type of vegetation and the type of soil.

4 Discussion and conclusions

The summary of basic statistics shows significant differences between the measurements on forested

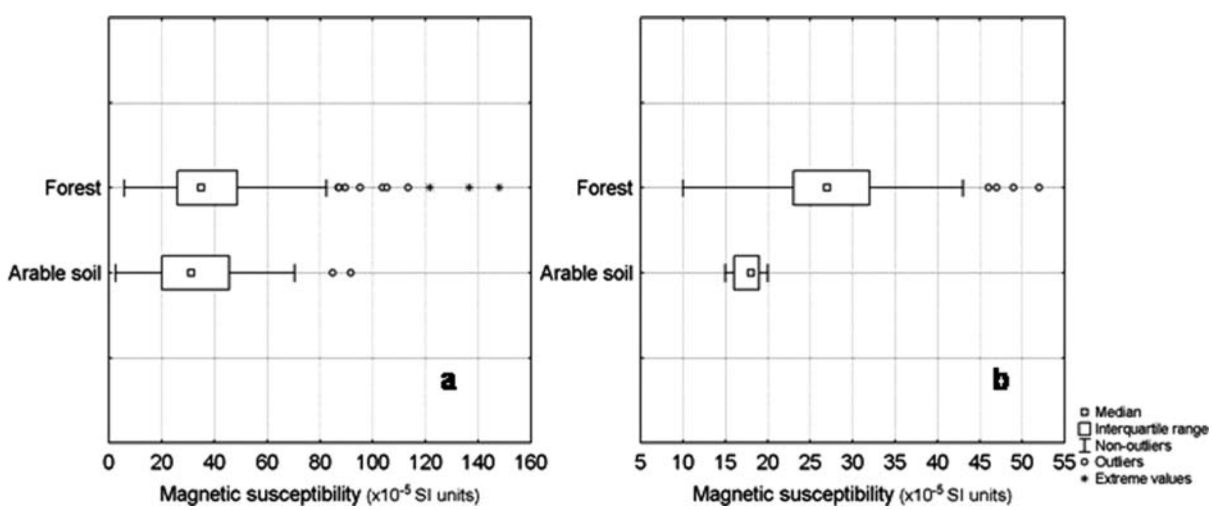

Fig. 5 Box and Whisker Plot for κ values: a) large area measurements, b) small area measurements.

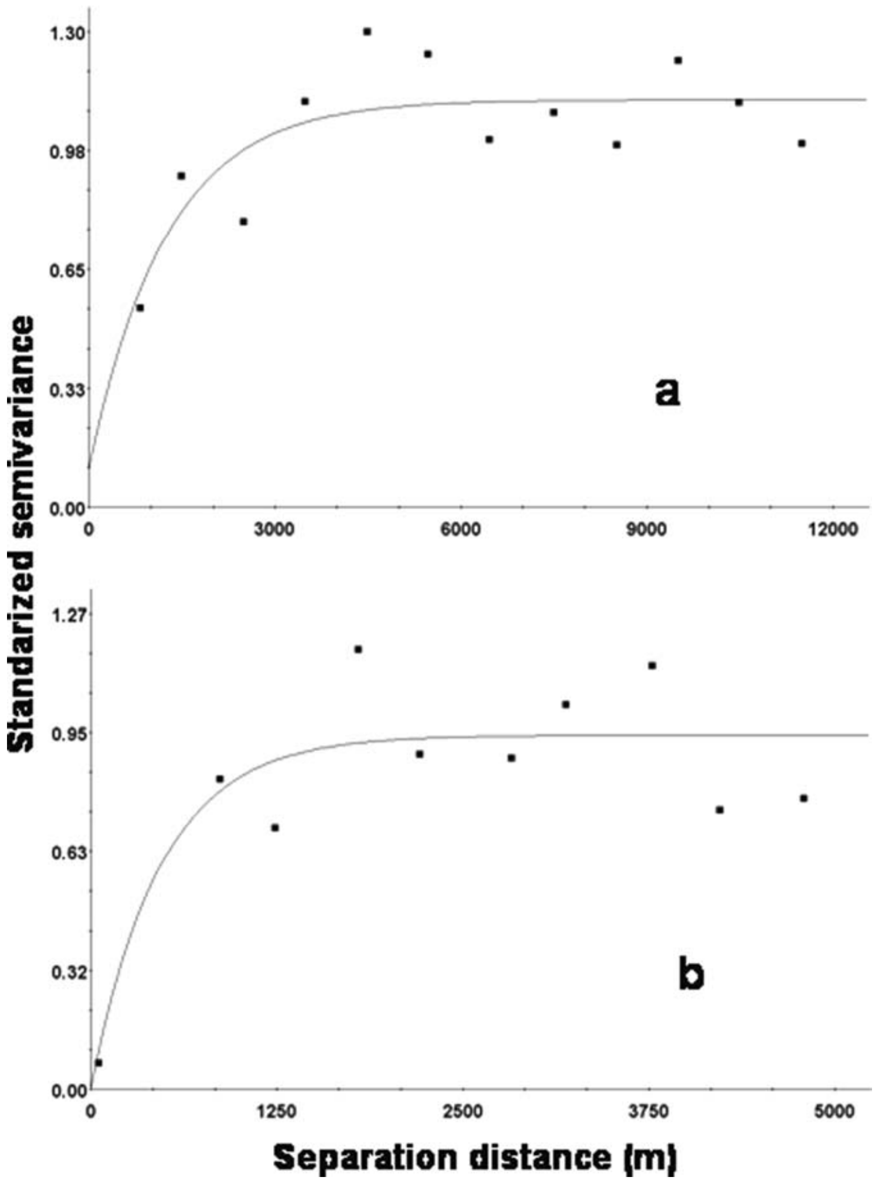

Fig. 6 The standardized semivariance (divided by standard deviations) calculated for κ values from measurements on large area: a) forest, b) arable soil. The black squares represent empirical values and solid lines show modeled values.

areas and arable land; thus results from both types of areas must be interpreted independently, and for proper environmental interpretation of the magnetic data the arable land must be distinguished clearly on the map.

The cultivated soil showed statistically significantly lower κ values. These are the result of "physical dilution" of magnetic particles in the uppermost 20 cm of arable layer, caused by annual ploughing. During high-resolution screening the arable areas must be avoided, even if the regularity of the measurement network will be considerably lower.

The information on spatial correlations is essential for the design of efficient sampling schemes, especially when the dust deposition is investigated in a large area, e.g. on a regional scale. This information can help one to make appropriate sampling decisions on the basis of cost-benefit criteria. The assessment of spatial dependences also helps in our understanding of the processes that occur during dust deposition in different areas.

In the range of natural κ values (below 30×10^{-5} SI units), the measurements in forested and arable areas were almost equal. This suggests that the natural magnetic background in topsoil is independent

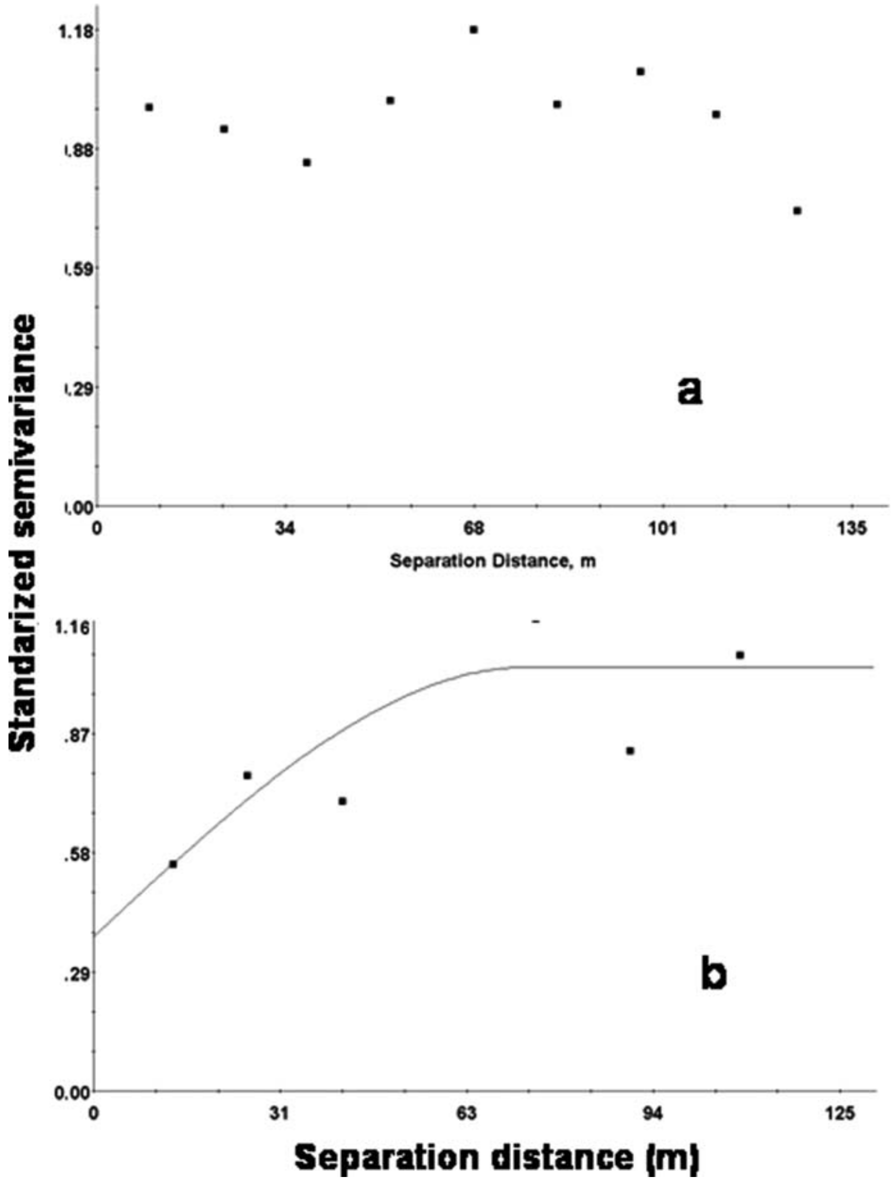

Fig. 7 The standardized semivariance (divided by standard deviations) calculated for κ values from measurements on large area: a) forest, b) arable soil. The filled squares represent empirical values and solid lines show modeled values.

of vegetation cover. The noticeable differences were observed for anthropogenic values (over 30×10^{-5} SI units). This is a result of different deposition conditions and different agrotechnical activity in forest and open areas.

The semivariograms obtained were thoroughly modeled using positive-definite models as shown in Figs. 6 and 7. The exception was semivariogram for susceptibility measurements in small forest area. This was too complicated for accurate modeling. One can see that the types and parameters of semivariograms reflect both the scale of observations and type of land use.

In the case of measurements in large area the exponential model was the best – both for forest and arable soil measurements. The range of influence determined from semivariogram modeling was distinctly greater for forest area data (about 3–4 km) than for arable land (about 1–1.5 km). This means that large-scale spatial correlations between susceptibility measurements have longer extent in forest than in arable land. Thus, spatial correlations should be taken into account when making magnetic susceptibility measurements, especially on a regional scale. From the above considerations, it follows, that grid size of spatial sampling in investigation on a regional scale in agricultural areas should be much denser than in forest ones.

The semivariance parameters, in particular the range of influence, should be incorporated into the susceptibility measurement analysis together with the basic statistical parameters. For example, the information on range of influence may be fundamental when susceptibility measurements are used as "soft data" in co-kriging analysis together with "hard data" e.g. geochemical measurements (Deutch and Journel, 1998; Webster and Olivier, 2001).

The semivariances calculated from small area measurements differ much more and show higher nugget effects in the semivariance compared to those calculated from large area measurements. The semivarince calculated from forest measurements has clear periodic form behavior (a hole effect), which often appears when repetitive or cyclic patterns are studied. Such semivariograms have been reported earlier when forest investigations were carried out (e.g Kirwan *et al.*, Zawadzki *et al.*, 2005). The observed cyclicity of semivariance probably reflects periodic dust deposition in forest stands caused by the arrangement of trees (or tree groups). The semivariance calculated from arable soil measurements is more regular and exhibits longer spatial continuity. In this case, the spherical model with range of influence equal to the ca. 70 m model was used to fit the semivariogram. It reflects a much more homogeneous distribution of dust deposition, which is the result of systematic ploughing of the field. The results obtained from small area measurements (e.g. in forest stands or in the arable land) suggest that during short-scale measurements, random variations in local environmental conditions become important giving rise to the nugget effect.

From the above considerations, one can conclude that the dust deposition of anthropogenic origin can be studied using in-field susceptibility measurements on a the regional and local scale. The level of anthropogenic pollution depends on the type of land use and generally speaking it is much higher in forested areas than in the arable land.

The large-scale spatial correlations in susceptibility measurements are generally stronger in forested areas than in arable land, which is caused by the accumulation properties of forest soils. At the same time, more variable forest environment means that short-scale susceptibility variations are higher in forest than in arable land. This problem, which is important for pollution monitoring of large area using magnetic screening techniques requires further investigation.

Acknowledgements This study was partially granted by Ministry of Education end Science the frame of project no 3 T09D 013 28.

References

Deutch, C.V. & Journel, A.G. (1998). *GSLIB: Geostatistical Software Library*. New York: Oxford University Press.

Goovaerts, P. (1997). *Geostatistics for natural resources evaluation*. New York: Oxford University Press.

Hansen, L.D., Silberman, D., & Fisher, G.L. (1981). Crystalline components of stack-collected, size-fractionated coal fly ash. *Environmental Science and Technology*, *15*, 1057–1062.

Heller, F., Strzyszcz, Z., & Magiera, T. (1998). Magnetic record of industrial pollution on forest soils of Upper Silesia (Poland). *Journal of Geophysical Research-Solid Earth*, *103*(B8), 17767–17774.

Hulett, L.D., Weinberger, A.J., Northcutt, K.J., & Ferguson, M. (1980). Chemical species in fly ash from coal-burnning power plant. *Science*, *210*, 1356–1358.

Isaaks, E.H. & Srivastava, R.M. 1989, *An introduction to applied geostatistics*. New York: Oxford University Press.

Kanji, G.K. (1993). *Statistical tests*. Stage Publications.

Kapička, A., Petrovsky, E., Ustjak, S., & Machackova, E. (1999). Proxy mapping of fly-ash pollution of silos around a coal-burning power plant: a case study In the Czech Republic. *Journal of Geochemical Exploration*, *66*, 291–297.

Kirwan, N., Oliver, M.A., Moffat A.J., & Morgan, G.W. (2005) Sampling the soil in long-term forest plots: The implications of spatial variations. *Environmental Monitoring and Assessment*, *111*, 149–172.

Magiera, T., Lis, J., Nawrocki, J., & Strzyszcz Z. (2002). *Magnetic susceptibility of Soils in Poland*. PIG Warszawa.

Magiera, T., Strzyszcz, Z., Ferdyn, M., & Gajda, B., MAGPROX team (2003). Screening of Anthropogenic Dust Pollutions in Topsoil by Using Magnetic Proxies. In: L. Pawlowski, M. Dudzinska & A. Pawlowski (Eds.), *Environmental engineering studies* (pp. 399–407). New York: Kluwer Academic/Plenum Publishers.

Schibler, L., Boyko, T., Ferdyn, M., Gajda, B., Holl, S., Jordanova, N., & Rosler, W., MAGPROX team (2002). Topsoil magnetic susceptibility mapping: Data reproducibility and compatibility, measurement strategy. *Studia Geophysica Et Geodaetica*, *46*, 43–57.

Strzyszcz, Z. (1993). Magnetic susceptibility of soils in the area influenced by industrial emissions. *Soil monitoring* (pp. 255–269). Monte Verita, Birkh(user Verlag, Basel.

Strzyszcz, Z. (1995). Gehalt an Ferromagnetika in den von der Immision der Zement-industrie in der Wojewodschaft Opole beeinflussten Böden. *Mitt. Deut. Boden. Ges.*, *76*, 1477–1480.

Strzyszcz, Z., Magiera, T., & Bzowski, Z. (1994). Magnetic susceptibility as an indicator of soils contamination in some regions of Poland. *Roczniki Gleboznawcze (Soil Scieince Annalysis) Supplement* t. **XLIV**, pp 85–93.

Strzyszcz, Z., Magiera, T., & Hellen, F. (1996). The influence of industrial immisions on the magnetic susceptibility of soils in Upper Silesia, Studia. *geoph. et geod.*, *40*, 276–286.

Thompson, R., & Oldfield, F. (1986). *Environmental magnetism*. London: Allen and Unwin.

Webster, R., & Olivier, M.A. (1990). *Statistical Methods in Soil and Land Resource Survey*. Oxford: Oxford University Press.

Webster, R., &. Olivier, M.A. (2001). *Geostatistics for environmental scientists*. Chichester, U.K.: J. Wiley & Sons, Ltd.

Zawadzki, J., Cieszewski, C.J., Zasada, M., & Love, R.C. (2005). Applying geostatistics for investigations of forest ecosystems using remote imagery. *Silva Fennica*, *39*(4), 559–617.