The influence of the wind direction and plants on the variability of topsoil magnetic susceptibility in industrial and urban areas of southern Poland

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Abstract Volume magnetic susceptibility (κ) was measured on the soil surface and in the vertical topsoil profile within a 300 km² area located in an urban-industrial conurbation. The results were compared to plant species compositions in the forest storeys, elevation above sea level, and terrain geomorphology. The content and mineral composition of the magnetic fraction were determined in the soil horizons. It was found that the extent of the area with enhanced topsoil magnetic susceptibility was similar to the dominant wind direction (south–west). Enhanced κ values were observed for the soil at the forest margin on the leeward side of the emitters as well as at sites located on exposed local elevations (≥ 10 m). There were no significant correlations between species composition of the forest stand and soil surface κ value (measured both with and without forest litter). Soil covered with deciduous trees—mostly ash (*Fraxinus excelsior* L.)—demonstrated higher κ values than soil under coniferous tree species. However, our results suggest that this parameter is not controlled by individual tree species, but rather depends on distance from emission sources, intensity of magnetic particle emission, and meteorological conditions (prevailing wind directions and dynamics).

Keywords Magnetic susceptibility · Technogenic magnetic particles · Pollution distribution · Forest topsoil

Introduction

Technogenic magnetic particles (TMPs) are constantly deposited on the surface of soil located in urban areas and their vicinity. These particles usually form during the solid fuel combustion (mostly coal) or high-temperature industrial processes (iron and non-ferrous metal industries, cokeries, cement and ceramic industries, etc.). The presence of TMP in topsoil is usually associated with increased concentration of potentially toxic metals carried by those particles. The metals are bound on the extended TMP surface by adsorption forces or incorporated in crystal lattice. TMPs mainly consist of iron oxides or occur in the form of ferrite crystal structures in which the metals partially substitute iron atoms (Magiera et al. 2011a). Consequently, the presence of TMPs in topsoil (mainly in the organic horizon) is considered an indicator for heavy metal soil pollution. This fact was confirmed by many authors (Veneva et al. 2004; Klose and Makeschin 2005; Spiteri et al. 2005; Blaha et al. 2008; Jordanova et al. 2008; Lu et al. 2008; Magiera et al. 2008; Bučko et al. 2011). Soil with natural plant cover, particularly forest soil, is often used as a target for magnetic susceptibility studies because it exhibits the stratigraphic sequence of the depositing dusts in undisturbed soil horizons for a long time. At present, in situ soil magnetometry is a verified method used for identifying anthropogenic magnetic “hot spots” and their correlations with geochemical anomalies (e.g. Thompson and Oldfield 1986; Petrovský and Ellwood 1999; Evans and Heller 2003; Magiera 2004; Strzyszc et al. 2006; Magiera et al. 2011b).

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Fig. 1 Location of studied area and sampling point. 1—forests and wooded areas, 2—Rybnik water reservoir, 3—main roads, 4—main railways, 5—selected regions (A, B, C): 1—pine, 2—beech, 3—birch, 4—oak, 5—maple, 6—ash, 7—larch, 8—spruce, 9—alder

Transportation of anthropogenic dusts in the environment proceeds in accordance with well-known mechanisms in which the wind dynamics and directions are most important (Matthias 1996). A large amount of such substances is intercepted when natural barriers (e.g. tree and bush groups, local elevations) appear in the pathway of pollutant flow. The dusts, including TMPs, deposited on leaves and needles are finally accumulated in the forest litter. The dusts are also found in the structures of tree bark and trunks, branches, leaves, needles, and roots (Kletetschka et al. 2003; Lehdorff et al. 2006; Klučiarová et al. 2008). The soil in the areas of increased (actual or historical) dust deposition exhibits high magnetic susceptibility. Nevertheless, it demonstrates high spatial variability, depending on many factors. One of them is the tree species, as different trees have various filtration properties (Strzyszc and Magiera 1998; El-Hasan et al. 2002; Ferdyn and Strzyszc 2003; Zawadzki et al. 2007, 2010; Łukasik et al. 2013).

The aim of this study was to determine the importance of the diverse species composition of the forest stand (in

the regions with increased dust depositions) in the distribution of topsoil magnetic susceptibility (κ) in the soil. The research was also performed in order to identify the areas in which local atmospheric conditions (wind directions) caused an increase in soil κ value in comparison with neighbouring areas.

Materials and methods

Environmental site description

The study area (coordinates: 18°23'19"E–18°40'08"E and 50°10'21"N–50°02'01"N; in total: 303.8 km²) was located in the Rybnik Plateau in the south-western part of Upper Silesia (Figure 1) in zone of mild temperate continental climate with average annual temperature +8 °C (+18 °C in July and −2 °C in January) and precipitation between 600 and 900 mm (SAM 2014).

The large 1775 MW power plant opened in 1972 and concentration of many other industrial sources (their

Fig. 2 Map of magnetic susceptibility (κ) measured directly on the soil surface. (1) Colour scale of κ ($\times 10^{-5}$ SI units), (2) Rybnik water reservoir, (3) main roads, (4) main railways, (5) measure points: (a) located ≥ 10 m AGL (b) ≤ 10 m AGL, (6) location of background point (1) and main emission sources: 2–10 urban and traffic sources (2—Rybnik Grabownia, 3—Rybnik Górka, 4—Rybnik Golejów, 5—Książenice, 6—Rybnik Lasoki, 7—Rybnik Centrum, 8—Rybnik Chwałęcice, 9—Lyski Zwonowice, 10—Jejkowice), 11—Rybnik

Power Plant, 12—Radlin Coke Plant, 13–16 old and closed steel plants (13—Rybnicka Kuźnia, 14—Silesia, 15—Ligocka Kuźnia, 16—Huta Gotartowska), 17–21 mining wastes storage facilities (17—Beatensglück, 18—Karol, 19—Anna, 20—Chwałowice, 21—Jankowice), 22–28 coal mines and electrical power and heating plant CHP (22—Anna, 23—Marcel, 24—Rymer, 25—Hyom, 26—Chwałowice, 27—Jankowice, 28—Żory)

location is presented in Figs. 2 and 3) as well as thousands of households using coal for heating caused that the annual total dust emission in the end of 1980s was in Rybnik 35 g m^{-2} and in 1999 it was even 45 g m^{-2} . After closing some old plants and modernization of others including application of high efficient precipitators, the annual dust emission was reduced to the amount of 3.2 g m^{-2} in 2013 (Magiera et al. 2015).

Brunic Arenosols dominated over *Luvisols* and *Cambisols* in the study area. *Dystric Cambisols*, *Endoeutric Cambisols*, *Luvisols*, and *Fluvi Gleysols* occurred mainly in the southern and south-western part of the study area, whereas *Haplic Podzols* and *Haplic Arenosols* were observed in its northern part. *Haplic Fluvisols* were found in the Ruda River valley and, sporadically, in the Rybnik Reservoir surroundings. The soils were formed on the Pleistocene gravels and sands (Pietrzykowski et al. 2010).

The most commonly observed tree species was pine (*Pinus sylvestris* L.), with admixtures of beech (*Fagus sylvatica* L.) and birch (*Betula pendula* Roth). Deterioration of tree-stand quality was found on the forest margins, where increased soil κ value was observed. Some of the pines and birches growing on the windward side had damaged assimilation apparatuses and thinned tree crowns. The process of tree weakening in the Rybnik Agglomeration vicinity under the influence of pollutant emission was described in detail by Harabin et al. (1980). The following tree species were very seldom found in the study area, listed in descending order: oak (mainly *Quercus robur* L.), maple (*Acer platanoides* L.), alder (*Alnus glutinosa* L.), larch (*Larix decidua* Mill. ssp. *decidua*), ash (*Fraxinus excelsior* L.), poplar (*Populus tremula* L.), and spruce (*Picea abies* (L.) Karsten). Birch (*Betula pendula* Roth) was the dominant species in woodlands and coppices. The

Fig. 3 Map of magnetic susceptibility (κ) measured after Oi subhorizon removal. Refer to Fig. 2 caption for more details

understorey was mainly formed by pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth) undergrowth. Often, there was neither understorey nor groundcover in the lower forest storeys. Various grass species dominated over bilberry (*Vaccinium myrtillus* L.) in the groundcover. Ferns (*Pteridium aquilinum* (L.) Kuhn) and mosses (*Polytrichum commune* Hedw.) were less often. The forest litter was mainly composed of leaves and (to a lesser extent) needle cover, pine-cones, and small sticks. As routine works related to the forest growing, protection, and organization were performed, there were sites without forest litter or humus, and also ploughed soil spots.

Methods of study

The topsoils (up to 25 cm depth) found in the forests and wooded areas were examined. The researchers created a grid of 515 measurement points (average distance between points: 350 m), at which the volume magnetic susceptibility (κ) was measured on the soil surface. The κ measurements were taken with a Bartington MS2D sensor (with detection limit 0.1×10^{-5} SI units) according to the

procedure described by Schibler et al. (2002). The magnetic susceptibility measurements were correlated with the GPS geographic coordinates. Two κ measurement series of every point were performed, i.e. with and without forest litter (after the Oi subhorizon removal). Each measurement result was the arithmetic mean obtained from 10 to 20 individual κ value measurements taken within a circle (radius approximately 1.0 m).

The average magnetic susceptibility κ and the content of the magnetic fraction in it were calculated with the arithmetic mean. The main descriptive statistics of the measured quantities are given in Table 1. The mean soil κ value was calculated in different sections of AMSL (above mean sea level) and AGL (above ground level) altitudes (Table 2). Isolines of the κ values with and without forest litter (Figs. 2 and 3, respectively) were prepared for the forests and wooded areas. The main wind directions and its average speed (Fig. 4) in the study area were defined with the available air quality measurement results (SAM 2014).

The dominant type of vegetation and individual tree species in the defined plant groups (representing particular forest storeys) were identified for each measurement point

Table 1 Basic statistic parameters of magnetic susceptibility measured directly on the soil surface (with litter) and after the litter removal (without litter)

Statistics/area	Magnetic susceptibility (κ) ($\times 10^{-5}$ SI)		Magnetic fraction without litter (in wt %)
	With litter	Without litter	
<i>Study area</i>			
Number of sites (n)	515	515	43
Average	32.5	51.2	4
Median	26.1	42.4	2.8
Range	5.8–192.1	12.0–315.0	0.3–26.2
Standard deviation	21.6	33.8	4.5
Coeff. of skewness	2.8	3.4	3.7
Correlations			
Pearson	[1:3] = 0.21 <i>p</i> = 0.175	[1:2] = 0.89	[2:3] = 0.62
Spearman	[1:2] = 0.99	[1:3] = 0.99	[2:3] = 1.00

Table 2 Average soil magnetic susceptibility (κ) in relation to the altitude

Altitude	N	Magnetic susceptibility κ ($\times 10^{-5}$ SI)	
		With litter	Without litter
Absolute altitude (m.a.s.l.)			
>290	4	54.6	88.3
270–290	78	45.9	69.6
250–270	170	32.5	52.5
230–250	182	31.1	48.1
210–230	81	22.3	36.1
Relative (m)			
>10	51	46.0	73.1
Normal	449	31.2	49.2
<10	15	25.8	36.7
<i>Correlations between magnetic susceptibility and altitude</i>			
Absolute altitude			
Pearson	515	0.86*	0.83*
Spearman	515	0.99*	0.99*

* $p < 0.05$

of magnetic susceptibility. The mean κ value of the soil was calculated for the sites in which the plant groups occurred. Additionally, the correlation between the presence of these plant groups and soil κ value was examined using the Spearman's rank correlation coefficient (Table 3).

In the study area, there were 43 places in which the soil surface magnetic anomalies were observed. At those sites,

25-cm-deep soil cores were collected with the Humax soil probe. The magnetic susceptibility (κ) of each soil core was measured along its whole length (resolution 1 cm) with the Bartington MS2C sensor (with detection limit 0.1×10^{-5} SI units). The genetic horizons of the soil (Fig. 5) were characterized according to the WRB soil classification (IUSS 2007). The grain-size analysis was performed following the FAO procedure (Guidelines for soil description 2006). Samples taken from individual soil horizons and subhorizons of Humax cores were air-dried at room temperature and shaken through a set of sieves that have progressively smaller openings in a range of 2.0–0.05 mm. Material from each soil horizons and subhorizons in the cores was separated into magnetic (Mf) and non-magnetic fractions, and their weight percentages were determined. The separation was performed by using hand magnet. The mineral composition of the magnetic fraction was determined with X-ray analysis and reflected light microscopy. The results of the soil core examinations helped to characterize the pollution level of the soil with TMPs in the study area profile (Fig. 5).

Pearson's Chi-squared test, the Kolmogorov–Smirnov test, and the Shapiro–Wilk test (statistical significance level $p = 0.05$) were applied to assess the correctness of the average value calculation. The Pearson correlation coefficients and Spearman's rank correlation coefficients were used to identify correlations between all measured variables (Tables 1 and 2). Additionally, the statistical significance level p was calculated for the t test of the investigated variables; p values above are shown in Tables 1 and 2.

Results and discussion

Soil and forest floor characteristics

On the base of morphological analysis of topsoil cores, the following information about the composition and development of organic horizon and uppermost part of soil profiles was obtained. In the study area, the organic horizon was 2.2 cm thick (Fig. 5). It consisted of:

- The Oi₁ subhorizon with average thickness of 0.2 cm, composed from unchanged large parts of leaves and needle cover (observed on 93 % of the study area);
- The Oi₂ subhorizon with average thickness of 1.2 cm, containing pieces of primary forest litter, crushed like pipe tobacco (observed on 83 % of the study area);
- The fermentative Oe subhorizon with average thickness of 0.7 cm, composed mainly from fibrous and loosely crumbled rotten forest litter (observed on 79 % of the study area);

Fig. 4 Main wind directions (a) and wind speed (b) based on data from 2010 to 2013 in the area of study (SAM 2014)

- The humic Oa subhorizon with average thickness 1.1 cm, composed from highly decomposed and formless organic substances (observed on 79 % of the study area).

The border between O and Ah horizon was not sharp. In many cases the intermediate OaAh horizon (and less often the mixed Oa/Ah subhorizon) was observed. The morphology of the whole organic horizon indicated the presence of fresh and wet mor humus, and (less often) fresh moder in the study area.

The Ah horizon was found in 98 % of topsoils and its mean thickness was 3.8 cm (Fig. 5). It mainly consisted of loose medium- and coarse-grained sand (slightly gravelled) and gravel with large admixtures of black humic substance. It overlay the eluvial E horizon through the intermediate AhE horizon. The E horizon was found in 23 % of measurement points, only where *Podzols* and *Albic Cambisols* were found. The average thickness of the E horizon was

2.4 cm, and it was mainly composed of medium-grained sand and gravel. The E horizon contacted the illuvial B horizon through the visible colour change and a thin intermediate layer (0.5–1.5 cm). The B horizon was seen in 79 % of the soil profiles. Its mean thickness was 6.4 cm. It normally contained medium-grained sand and, to a lesser extent, gravels. The admixtures of iron compounds and, sometimes, loams cementing the skeletal grains were often found in this horizon. The bedrock C horizon was found in 9 % of the studied soil cores and was normally built from highly gravelled sand and gravels. The bedrock R horizon was not found in the very few pits and natural outcrops (up to the 1.3 m depth).

Most studied sites are of urban areas in which small patches of mixed-tree forest, woodlands, and coppices were found (Fig. 1). The coniferous forest stand dominated over the deciduous one in most of the study areas. Forest parts co-occurred with fairly diverse forest stands, particularly in the relatively large and small areas (regions A and C, respectively). Pine monoculture was observed in the B region (Fig. 1).

Magnetic susceptibility of soils

In the study area, the soil magnetic susceptibility (κ) was lower (measurement with forest litter) or comparable and lower (measurement without forest litter) than the soil κ values observed in other Polish and European industrial regions (Boyko et al. 2004; Schmidt et al. 2005; Fialová et al. 2006; Magiera et al. 2006a; Magiera and Zawadzki 2007; Wojas 2009). In the southern and central part of the study area, there were a few magnetic anomalies observed (i.e. regions in which the κ value was greater than 50×10^{-5} SI units—measured on the surface; Fig. 2). Following Strzyszczyk et al. (2006), if the κ value is above 50×10^{-5} SI units, the soil was considered severely threatened with the heavy metal pollution (heavy metals co-occurring with TMPs). The course (shape) of isoline 50×10^{-5} SI units and the range of the observed anomalies probably reflected the size of the dust pollutant clouds from the present and historical emitters (Fig. 2). In the case of measurements of magnetic susceptibility after the litter removal isoline 75×10^{-5} SI would be the better indicator (Fig. 3). The anomaly extent roughly followed the main wind direction (SW) observed in the study area in the past (Harabin et al. 1980) and at present (Fig. 4). Both in the study area and in all of Upper Silesia, the highest air pollutant concentrations are observed when anti-cyclonic circulation with dominant air advection from the S and SW directions occurs. Such concentrations are also measured when there is no air advection or there is air stagnation in the high-pressure area centre (Leśniok et al. 2010). A large number of windless days (25.9 %) and low average annual

Table 3 Average soil magnetic susceptibility (κ) in relation to vegetation cover

Group of plants	Magnetic susceptibility ($\times 10^{-5}$ SI)		Frequency %	Spearman correlation	
	1	2		1	2
Deciduous forest	40.1	62.4	38.8	0.23*	0.23*
Coniferous forest	27.6	43.9	61.2	−0.23*	−0.23*
Pine	27.7	44.0	59.2	−0.22*	−0.23*
Beech	41.8	64.2	18.6	0.21*	0.21*
Birch	35.6	55.4	8.5	0.03**	0.03**
Oak	33.1	51.3	4.1	0.03**	0.03**
Maple	35.2	54.3	3.5	0.04**	0.04**
Ash	124.5	204.6	1.2	0.16*	0.16*
Larch	27.5	44.0	1.4	0.00**	0.00**
Alder	24.6	38.8	2.1	−0.06**	−0.06**
Poplar	38.9	61.4	0.6	−0.05**	−0.05**
Shrubs	29.7	46.9	19.8	−0.06**	−0.06**
Brushwood trees	36.1	56.9	25.6	0.06**	0.06**
Without understory	32.2	50.4	55.5	0.02**	0.02**
Fern	22.9	36.4	4.5	−0.12*	−0.12*
Grass	29.2	46.7	41.0	−0.11*	−0.11*
Moss	33.0	51.5	1.4	0.01**	0.01**
Blueberry	24.9	39.6	14.8	−0.16*	−0.16*
Without undergrowth	39.6	62.0	38.3	0.28**	0.28**
Leaves	33.8	53.1	72.0	0.06**	0.06**
Needles	26.5	41.9	22.3	−0.16*	−0.16*
Without litter		65.8	5.2	0.16*	0.16*
Furrow soil	31.7	49.6	6.6	0.01**	0.01****
Marsh	36.7	57.2	2.9	0.05**	0.05**

* $p < 0.05$; ** $p > 0.05$

wind speed (e.g. 1.0–2.0 m/s and 1.7–3.5 m/s for past and present, respectively) cause dust deposition in the study area (Fig. 4). Furthermore, dust pollutant accumulation was also facilitated by the local land morphology: poorly ventilated basin and valleys predominate over the flat and upland forms. The accumulation was also aided by the fact that the temperatures observed in the upland regions were higher during the day and lower at night than the temperatures measured for the lower areas.

At some research points, the soil with increased magnetic susceptibility was found in the land adjoining the forest margin (Figs. 2 and 3). The size of these land parts was defined by the κ value isolines in the vicinity of some emitters (e.g. emitters 5, 6, 14–16, 20, 26–28; Figs. 2 and 3). Their shapes were similar to the shapes of forest areas or wind direction. This finding indicates an important role of the forest as a semi-permeable curtain for the dust and gaseous pollutant stream transported by wind from the emitters.

It was observed that soil magnetic susceptibility increased with the elevation of the ground surface above sea level (Table 2). Surface areas elevated higher than

10 m (AGL) demonstrated higher κ values than neighbouring areas (Figs. 2 and 3; Table 2). On the other hand, the κ values observed for the land located below the 10 m level were lower than in the neighbouring areas. The discussed correlations are in agreement with the already-mentioned important role of wind direction played in dust pollutant deposition and selective enrichment of topsoils with magnetic particles.

In the topsoils, a visible κ maximum was observed in the lower part of the organic horizon (OaAh) (Fig. 5). It was caused by the magnetic fraction present in the soil, which was confirmed by the statistically relevant correlation coefficient values (Table 1). It was also proven by the similar course of the changes in soil κ values and the magnetic fraction content in the soil profile (Fig. 5). The magnetic fraction was composed of magnetite ferrospheres, cenospheres of not fully burnt organic matter and, to a lesser extent, isometric particles of hematite and maghemite, particles of the pyrite/goethite pseudomorph, and even small particles of metallic iron (α Fe) (Fig. 6). Concentrations of such particles are generally considered indicators of technogenic pollutants brought about by fossil

Fig. 5 Average distribution of magnetic susceptibility (Ms) and magnetic fraction content (Mf) in soil profile, including information concerning the grain-size fractions (CB—cobbles, COS—coarse sand, G—gravel, GS—gravel, and sand, MS—medium sand) and contents of magnetic minerals in Mf (α —magnetite ferrospheres $\gg$ isometric particles of hematite = and maghemite $\gg$ pyrite/goethite pseudomorphs and metallic iron, β —isometric particles of magnetite > hematite, γ —isometric particles hematite > magnetite)

fuel combustion and steel works activities (Thompson and Oldfield 1986; Kapička et al. 2001; Evans and Heller 2003; Boyko et al. 2004; Spiteri et al. 2005; Magiera et al. 2006a, b, 2007, 2008; Rothwell and Lindsay 2007). The effect of natural pedogenic processes that were sometimes observed in *Podzols* or *Gleysols* (Magiera et al. 2006a) in studied soil profiles was not detected.

There was little or no correlation between the species composition of the plant groups in the forest storeys and soil magnetic susceptibility (both measured with and without forest litter; Table 3). Nevertheless, there were significant differences between soil κ values in the areas where those plants grew. Soil covered with deciduous trees demonstrated higher magnetic susceptibility than soil covered with coniferous trees. This same regularity has already been observed in the vicinity of other European urban-industrial areas (Ferdyn and Strzyszc 2003; Zawadzki et al. 2007). The highest κ values were found at the site where ash (*Fraxinus excelsior* L.) grew. Nonetheless, it was not caused by the botanical predispositions of the trees, but resulted from the close location of a large TMP emitter (point 27; Figs. 2 and 3) and the prevailing

wind direction and dynamics (Fig. 4). The ash grew only in one area (region C; Fig. 1), co-occurring with pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth). Large numbers of pines and birches were also found in another research region (region A; Fig. 1), but they did not affect the increase in the soil magnetic susceptibility. In the same region, the tree species was highly varied, but this did not significantly influence the topsoil κ value. On the other hand, soil magnetic susceptibility was not uniform (Fig. 2 and 3) in the region where only pines grew (region B; Fig. 1). Apart from the ash-growing site, a relatively high topsoil κ value was observed in the areas where beech (*Fagus sylvatica* L.) and poplar (*Populus tremula* L.) occurred (Table 3). The lowest soil magnetic susceptibility was measured at the sites where spruce (*Picea abies* (L.) H. Karst) and alder (*Alnus glutinosa* L.) were found.

The plant groups making up the understorey did not significantly influence the magnetic susceptibility of the topsoil on which the plants grew (Table 3). The topsoil κ value at the places without groundcover or forest litter was higher than at the sites in which they were found. Low soil magnetic susceptibility was observed at the spots in which

Fig. 6 Magnetic fraction from soil horizon. **a**—Ferrosphere with dendritic magnetite crystallites (*ma*) in Ah horizon, **b**—cenosphere (*ce*) in Oe subhorizon, **c**—isometric magnetite (*ma*) and hematite (*he*) in b horizon, **d**—pyrite (*py*) with coke (*ck*) grain in Oi subhorizon

needle cover was found in the forest litter and at which ferns grew (*Pteridium aquilinum* (L.) Kuhn). The higher κ value of the soil covered with deciduous forest litter resulted from two factors. Firstly, dusts were more often emitted in the direction of the forest dominated by deciduous species. Secondly, deciduous trees are more efficient in intercepting dust particles from the pollutant stream than coniferous trees. Magnetic particles are found in the leaf and needle structures of various tree species (Schädlich et al. 1995; Matzka and Maher 1999; Hanesch et al. 2003; Ubat et al. 2004; Gautam et al. 2005; Lehdorff et al. 2006; Maher et al. 2008; Sagnotti et al. 2009). However, these are few inclusions of single particles without any significant influence on soil magnetic susceptibility.

Conclusions

In the Rybnik Agglomeration, the following soil magnetic susceptibility (κ) anomalies were observed:

- The extent of the area defined by the isolines with high soil κ values overlapped with the dominant wind directions (SW);

- The enhanced topsoil κ value was found on the forest margins on the leeward side of the pollutant emitters;
- The topsoil κ value was higher at the sites located at relatively higher elevations.

In the soil organic horizon, there was a large content of particles of magnetite $\gg$ hematite = maghemite $\gg$ pyrite/goethite pseudomorphs and metallic iron, which might attribute to the technogenic enhancement in topsoil magnetic susceptibility κ in the study area.

There was insignificant correlation or no correlation between the species composition of the forest storeys and the soil magnetic susceptibility κ measured with and without forest litter. The soil covered with deciduous trees (particularly ash) had higher magnetic susceptibility than the topsoil on which coniferous trees grew. Nonetheless, the correlation did not depend on the filtration properties of trees. It resulted from the fact that most of the local pollution sources were surrounded by deciduous forest complexes.

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