Tracing of traffic-related pollution using magnetic properties of topsoils in Daejeon, Korea

Seungwoo Lee¹ · Seoyeon Kim¹ · Hyeji Kim¹ · Youlee Seo¹ · Yeoncheol Ha¹ · Hanul Kim² · Raegyung Ha² · Yongjae Yu^{1,2}

Received: 9 April 2020 / Accepted: 21 September 2020 / Published online: 16 October 2020
© The Author(s) 2020

Abstract

The present study was designed to explore the possibility of roadside pollution screening using magnetic properties of topsoil samples in Daejeon, South Korea. Low-field magnetic susceptibility, frequency dependence of magnetic susceptibility, susceptibility of anhysteretic remanent magnetization, isothermal remanent magnetization (IRM) acquisition and demagnetization, back-field IRM treatment, and thermal demagnetization of composite IRM were determined for roadside topsoil samples. Magnetic susceptibility measured on 238 samples from the upper 5 cm of the topsoils ranged from 8.6 to 82.5×10^{-5} SI with a mean of $28.3 \pm 10.8 \times 10^{-5}$ SI. The proximal zone, 55 m wide area situated on either side of the main street, exhibited an enhancement of magnetic susceptibility. In areas distant from the main street, low magnetic susceptibility ($< 50 \times 10^{-5}$ SI) was observed. The topsoil samples exhibited significant susceptibility contrasts, suggesting that two dimensional magnetic mapping was effective in identifying traffic-related pollution. A few magnetic hotspots with intensities of magnetic susceptibility near or over 50×10^{-5} SI might reflect the difference in topographic elevation and surface morphology. Among various IRM-related parameters, remanence of coercivity was most significant statistically. In most samples, IRM component analysis provided dual coercivity components. Thermal demagnetization of composite IRM and morphological observation of magnetic separates suggest angular magnetite produced by vehicle non-exhaust emissions spherical magnetite derived from exhaust emission to be the dominant contributors to the magnetic signal. It is likely that lower- and higher-coercivity components represent the presence of coarse-grained angular magnetite and fine-grained spherical magnetite, respectively.

Keyword Roadside pollution · Environmental magnetism · Magnetic susceptibility · Magnetic coercivity · Magnetite

Introduction

Soil contamination or soil pollution poses a serious global threat to our environment. Increased concentration of soil pollutants should be of concern worldwide because of their toxicological impacts on ecosystems. In particular, heavy metals can cause severe adverse effects on any non-targeted

organism. It is generally considered that heavy metals accumulated in soils are derived from natural lithogenic or artificial anthropogenic sources (e.g., Karimi et al. 2017). In the absence of heavy industry, roadside dust is undoubtedly the most common sources of environmental pollution in urban areas (e.g., Bučko et al. 2011). Recently, the applicability of magnetic monitoring has increasingly been applied for the evaluation of anthropogenic pollution (e.g., Bučko et al. 2010).

Geochemical investigation provides the highest resolution in environmental studies in terms of quantitative evaluation of the degree of pollution as well as qualitative assessment of the pollution sources (e.g., Jordanova et al. 2013). However, geochemical investigation requires a great deal of chemical analyses, which are time-consuming, expensive, and destructive. In contrast, magnetic methods are rapid, cost effective, and non-destructive (e.g., Evans and Heller 2003). In practice, magnetic techniques provide a descent basis for

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s12665-020-09223-9>) contains supplementary material, which is available to authorized users.

✉ Yongjae Yu
yongjaeyu@cnu.ac.kr

¹ Department of Geological Sciences, Chungnam National University, Daejeon 34134, Korea

² Department of Astronomy, Space Science and Geology, Chungnam National University, Daejeon 34134, Korea

a comprehensive geochemical investigation. Among various rock magnetic approaches, magnetic susceptibility is the most widely used tool to map and monitor the heavy metal pollution of soils (e.g., Hanesch et al. 2007; Yang et al. 2007, 2009; Blaha et al. 2008; Karimi et al. 2011, 2017; Dankoub et al. 2012; Ayoubi et al. 2019a, b; Ayoubi and Adman 2019; Ayoubi and Karimi 2019). Magnetic susceptibility reflects the amount of paramagnetic and ferromagnetic minerals in rocks and soils (e.g., Evans and Heller 2003).

In general, magnetic minerals present in soils have three distinctively different origins. First, unpolluted soils contain lithogenic magnetic minerals that were the product of weathering and transportation of parent rocks. Second, pedogenic process under aerobic conditions is responsible for the enhancement of magnetic susceptibility, by increasing the concentration of nano-sized magnetite and/or maghemite (e.g., Torrent et al. 2010; Liu et al. 2012; Ayoubi and Karami 2019). Third, polluted soils commonly contain significant amount of anthropogenic magnetic minerals. Presence of highly magnetic particles in polluted soils originates from anthropogenic contribution. Urban airborne particulates are enriched in heavy metals, acting as carriers of potentially hazardous heavy metals (e.g., Boyko et al. 2004). Magnetic properties have been used as a proxy for the heavy metal concentrations in soils (e.g., Hanesch and Scholger 2002; Jelenska et al. 2004; Schmidt et al. 2005; Dong et al. 2014; Grison et al. 2015; Ayoubi and Karimi 2019). Such a linkage came from the fact a combustion process is responsible for the enhancement of magnetic particulates and heavy metals in soils (e.g., Tolonen and Oldfield 1986). Therefore, soil magnetometry is useful as a first-order constraint on the degree of heavy metal pollution (e.g., Bučko et al. 2010; Ayoubi et al. 2019a, b).

In industrial regions, fine-grained magnetic particulate matters are produced by combustion of fossil fuels and other high temperature technogenic processes (e.g., Hanesch et al. 2003; Spiteri et al. 2005; Jordanova et al. 2006; Yan et al. 2011; Zhang et al. 2011; Zhu et al. 2013). On the other hand, the most important source of heavy metal pollutants in urban environments is roadside dust emission (e.g., Muxworthy et al. 2001; Gautam et al. 2004; Lu and Bai 2006; Kim et al. 2007; Lu et al. 2007; Werkenthin et al. 2014; Ojha et al. 2016). For instance, the primary constituent of automobile exhaust was found to be associated with magnetic particles. In addition, exterior rusting, internal exhaustion, and ablation of breaks also produce fine-grained magnetic particulate matters (e.g., Petrovský et al. 2000; Wawer et al. 2015; Ma et al. 2016). Thus, rock magnetic proxies have been applied to traffic-related roadside dusts (e.g., Prajapati et al. 2006; El-Hasan 2008; Maher et al. 2008; Lu et al. 2011; Nikolaeva et al. 2017; Pierwola et al. 2020). However, the correlation between pollutants and magnetic proxy was far from being a simple linear relation (e.g., Chaparro et al. 2004). As a

result, it was necessary to generate magnetic mapping at a regional scale to assess the spatial distribution of pollutants for each independent investigation (e.g., Ayoubi and Adman 2019).

A regional scale magnetic investigation on roadside dust is rare in Korea (Kim et al. 2007). In this study, we tested magnetic measurements as a proxy to monitor the degree of roadside pollution. The main objective of this work was to identify detailed characteristics of the magnetic materials derived from circulation of traffic-derived roadside soils in Daejeon, South Korea. To unravel magnetic signal on the roadside dusts, low-field magnetic susceptibility, frequency dependence of magnetic susceptibility, susceptibility of anhysteretic remanent magnetization, isothermal remanent magnetization (IRM) acquisition and demagnetization, back-field IRM treatment, and thermal demagnetization of composite IRM will be carried out. In particular, we focused on the mutual relation between various high-field IRM-related properties.

Methods and materials

Description of the study area and sampling

South Korea is located in a transition zone between the humid subtropical zone and the humid continental climate zone. The monsoon-influenced climate is dominant over the summer and brings about 80% of the annual rainfalls. Daejeon is South Korea's fifth-largest metropolis with a population over 1.5 million (Fig. 1). In 2019, annual precipitation from rainfalls (and snowfalls) in Daejeon was 1458.6 mm. According to climate data from 1981 to 2010, monthly mean temperatures of Daejeon ranged from -1.0°C in January to 25.6°C in August. The mean elevation of Daejeon is 70 m a.s.l. A Jurassic two mica granite constitutes the basement of Daejeon area (Hwang and Moon 2018).

The meteorological parameters on the sampling date (June 28, 2019) were available from the Korea Meteorological Administration (<https://www.weather.go.kr/>). In detail, temperature ranged between 22.1 and 29.9°C , while humidity was 76.3%. The prevailing wind directions on June 28, 2019 were SE and SSE, with low wind speeds of 1.5 m/s.

The Hanbat-daero is a major twelve-way street (Fig. 1), with the daily traffic volume over 100,000 vehicles on weekdays. It is not awkward to witness a heavy traffic queue during rush hours. The stream bridge (Yuseong-daegyo) is a street-stream crossroad, which is about 500 m away from the highway entrance. The deck height of the stream bridge is about 5 m. At ground level of the bridge, there is a grassland, where we expect to check spatial variation of traffic-related pollution (Fig. 1). We set the base station (star symbol in Fig. 1) near to the main street ($36^{\circ}21'32.19''\text{N}$,

Fig. 1 In situ magnetic susceptibility traverses across urban street in Daejeon, South Korea measured on June 28, 2019. Magnetic susceptibilities were measured from a total of six profiles (N1, N2, N3, S1, S2, and S3). Each profile was 100 m long, set to be nearly perpendicular to the twelve-way street along the river. The inset was generated

from the “Generic Mapping Tools (GMT)” version 6.0.0 (released on November 1, 2019) distributed from the School of Ocean and Earth Science and Technology, University of Hawaii at Manoa (<https://gmt.soest.hawaii.edu/>). We set the base station (star symbol) near to the main street (36°21′32.19″N, 127°21′27.49″E).

127°21′27.49″E). It is likely that vehicles are the only significant source of pollution in the grassland, because there is no nearby agricultural or industrial facilities (Fig. 1).

Magnetic susceptibilities were measured from a total of six profiles, three towards the south and three towards the north (Fig. 1). Each profile was 100 m long along the river, set to be nearly perpendicular to the twelve-way street (Fig. 1). Three profiles towards the south were separated by 5 m with one another, labeled as S1, S2, and S3. Similarly, three profiles towards the north were labeled as N1, N2, and N3. The net investigation area covered about 2000 m² (200 m long and 10 m wide).

Magnetic susceptibilities were measured using a portable magnetic susceptibility meter ZH-instruments SM30 with a sensitivity of 10⁻⁷ SI. A total of 238 readings were taken (40 from S1, 31 from S2, 32 from S3, 40 from N1, 54 from N2, 41 from N3). Each data point was double or triple checked to ensure the reproducibility of signal. A total of 76 representative sites were selected (13 from S1, 10 from S2, 10 from S3, 13 from N1, 18 from N2, 12 from N3), where we collected samples from the upper 5 cm of the topsoils. These 76 sites were picked on the basis of magnetic susceptibility measurements including sites from the highest,

lowest, and median (or mean if necessary) susceptibilities. The topsoils were un-stratified with loose, brown fine- to medium grains sand with occasional fine gravels. Whenever encountered, we discarded gravels. Samples were collected using a stainless steel trowel, and stored in a non-magnetic one-inch cube. Collected soil samples were placed in a sealed polyethylene bags and transported to the laboratory for further measurements. For these plastic cubes, magnetic susceptibilities were measured in the lab using a Bartington MS2 susceptibility bridge.

Presence of void induces grain motions in a plastic cube, resulting in inconsistent magnetic behavior. To prevent possible grain motions during magnetic measurements on spinning magnetometers, non-magnetic paraffin was used. It is well-known that non-magnetic solid paraffin has a melting point of ≈40 °C. We injected liquid paraffin into empty spaces of plastic cubes and dried overnight. The remanent magnetization of a one-inch plastic cube with full paraffin had remanent magnetization 3000 fold lower than the weakest soil samples. Hence, the influence of paraffin injection was magnetically insignificant in the present study. Samples were weighed, and then stored in a refrigerator to minimize the effect of drying or moisturizing.

Laboratory analyses

Magnetic susceptibilities (χ) were measured at low (0.46 kHz; χ_{lf}) and high frequencies (4.6 kHz, χ_{hf}) using a Bartington MS2 dual frequency sensor. The frequency dependence (χ_{fd}) was calculated as χ_{fd} (%) = $[(\chi_{lf} - \chi_{hf})/\chi_{lf}] \times 100$ to address the relative contribution of the superparamagnetic (SP) particles in the total magnetic fraction of the soils (Dearing et al. 1996).

Anhyseretic remanent magnetization (ARM) is produced when a steady external field is superimposed on a decaying alternating-field (AF). The susceptibility of ARM was determined as $\chi_{ARM} = ARM/B_{ARM}$ for a field B_{ARM} of 0.05 mT or $500/4\pi = 39.8$ A/m (Table 1).

To eliminate the influence of initial state dependence of remanent magnetization, samples were AF demagnetized to 100 mT before each isothermal remanent magnetization (IRM) treatment. All the remanent magnetizations were determined using an AGICO JR-6 spinner magnetometer.

IRM was acquired along z at 18 steps of 1, 2, 5, 10, 20, 25, 30, 40, 50, 60, 80, 100, 120, 150, 200, 300, 500, 1000 mT using an ASC-Scientific IM-10–30 impulse magnetizer. AF demagnetization was carried out at 15 steps of 1.0, 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 20.0, 25.0, 30.0, 40.0, 45.0, 50.0, 60.0, and 80.0 mT using an AGICO LDA5 AF demagnetizer. On completion of AF demagnetization of IRM, IRM was produced again by exposing samples in a field of 1 T. Then, back-field IRM was applied along negative z at 18 steps of 1, 2, 5, 10, 20, 25, 30, 40, 50, 60, 80, 100, 120, 150, 200, 300, 500, 1000 mT. Note that IRM was produced along positive z , while back-field IRM was applied along negative z , to avoid the possible effect of remanence anisotropy.

All the samples showed saturation by 300 mT, hence the IRM applied at 1 T can be treated as saturation IRM (SIRM). Classical backward S -ratio compares the SIRM acquired in a saturation field (e.g., 1 T) with the IRM in a smaller back-field (e.g., -300 mT) as $S = IRM_{-0.3\text{ T}}/SIRM$ (Stober and Thompson 1979). Revised backward S -ratio was modified

Table 1 Magnetic Properties of 26 Soil Samples

Sample	χ_{fd} (%)	χ_{ARM} (10^{-5} SI)	MAF (mT)	B_{cr} (mT)	$S_{0.1\text{ T}}$	$S_{-0.1\text{ T}}$	$S_{-0.3\text{ T}}$	HIRM	MIRM	MDF (mT)	B_R (mT)	P
GCA01	1.68	36.8	61.0	40.5	0.691	0.778	0.959	0.041	0.182	12.9	31.0	0.236
GCA05	1.63	36.4	69.2	47.5	0.663	0.779	0.950	0.008	0.214	12.4	32.8	0.242
GCA08	2.11	36.7	68.7	38.5	0.699	0.793	0.991	0.009	0.198	14.4	34.5	0.256
GCA15	0.84	146.6	57.6	31.8	0.745	0.765	0.938	0.034	0.201	8.1	21.1	0.179
GCA26	3.66	21.7	60.2	39.3	0.638	0.761	0.940	0.014	0.225	19.6	36.2	0.303
GCA37	3.88	17.1	77.5	38.2	0.638	0.777	0.957	0.016	0.208	20.4	42.8	0.261
GCB11	1.20	38.0	79.4	60.1	0.629	0.683	0.989	0.011	0.306	45.2	64.0	0.394
GCB18	4.09	58.4	57.8	29.6	0.717	0.799	0.965	0.035	0.166	23.9	32.4	0.316
GCB29	4.00	13.3	98.9	30.8	0.502	0.794	0.954	0.046	0.160	8.5	27.7	0.154
GCC01	1.37	56.2	57.9	36.4	0.805	0.856	0.973	0.027	0.117	12.4	28.1	0.218
GCC06	1.20	109.2	53.7	37.3	0.783	0.834	0.978	0.022	0.144	17.4	30.3	0.248
GCC12	3.66	25.2	49.7	35.0	0.787	0.783	0.939	0.027	0.190	13.1	28.9	0.258
GCC31	3.21	63.6	45.9	29.4	0.785	0.865	0.979	0.021	0.113	7.4	23.0	0.228
GCD04	0.93	79.3	62.0	29.9	0.682	0.855	0.946	0.054	0.091	7.4	25.6	0.208
GCD11	1.96	57.1	53.3	33.8	0.748	0.839	0.972	0.028	0.132	15.4	27.7	0.286
GCD15	4.17	54.6	39.3	29.0	0.834	0.864	0.967	0.033	0.103	11.0	23.2	0.239
GCD31	0.99	105.3	33.7	27.1	0.813	0.864	0.960	0.040	0.096	8.2	19.1	0.231
GCD40	1.13	115.2	39.6	23.7	0.728	0.848	0.948	0.052	0.100	10.4	21.6	0.254
GCE01	1.26	66.3	53.9	33.3	0.784	0.864	0.981	0.019	0.117	13.0	26.3	0.222
GCE18	3.33	29.1	48.5	30.0	0.732	0.835	0.981	0.045	0.121	13.8	26.7	0.265
GCE30	4.29	27.9	51.8	29.7	0.686	0.896	0.972	0.017	0.087	11.1	23.3	0.251
GCE44	1.00	24.1	35.9	25.2	0.806	0.889	0.984	0.016	0.095	9.8	20.5	0.258
GCF01	1.15	41.7	55.1	32.5	0.720	0.825	0.970	0.030	0.145	9.3	24.2	0.198
GCF15	2.55	28.2	48.4	29.3	0.713	0.850	0.939	0.061	0.090	5.4	20.3	0.158
GCF35	0.57	85.1	49.8	29.0	0.739	0.855	0.961	0.057	0.088	6.3	20.6	0.203
GCF36	1.67	60.6	52.8	34.0	0.725	0.846	0.982	0.018	0.136	18.7	30.8	0.304

χ_{fd} (%) = $[(\chi_{lf} - \chi_{hf})/\chi_{lf}] \times 100$; χ_{ARM} susceptibility of anhysteretic remanent magnetization; MAF median acquisition field; B_{cr} coercivity of remanence; $S_{0.1\text{ T}} = IRM_{0.1\text{ T}}/SIRM$; $S_{-0.1\text{ T}} = 0.5 (1 - IRM_{-0.1\text{ T}}/SIRM)$; $S_{-0.3\text{ T}} = 0.5 (1 - IRM_{-0.3\text{ T}}/SIRM)$; HIRM = 0.5 ($SIRM + IRM_{-0.3\text{ T}}$); MIRM = 0.5 ($SIRM + IRM_{-0.1\text{ T}}$) - HIRM; MDF median destructive field; B_R Crossover field; P Crossover point

as $S_{-0.1\text{ T}} = 0.5 (1 - \text{IRM}_{-0.1\text{ T}}/\text{SIRM})$ and $S_{-0.3\text{ T}} = 0.5 (1 - \text{IRM}_{-0.3\text{ T}}/\text{SIRM})$ (Bloemendal et al. 1992; Liu et al. 2007). While S varies from -1 to $+1$, $S_{-0.1\text{ T}}$ or $S_{-0.3\text{ T}}$ varies from 0 to $+1$. In particular, it has been widely used that values of $S_{-0.3\text{ T}}$ in percent represent the amount of low coercivity fraction in samples. The forward S -ratio compares the SIRM acquired in a saturation field (i.e., 1 T) with the IRM in a smaller forward field (e.g., 100 mT) as $S_{0.1\text{ T}} = \text{IRM}_{0.1\text{ T}}/\text{SIRM}$ (Kruiver and Passier 2001). A complementary statistical treatment and physical rationale on the use of S -ratio are beyond the scope of this study, but were provided by Liu et al. (2007) and by Heslop (2009), respectively. In addition to the various forms of S ratio, two other coercivity-related parameters were useful (e.g., Bloemendal et al. 1992; Yamazaki et al. 2003). First, high-coercivity fraction of IRM (HIRM) was defined as $\text{HIRM} = 0.5 (\text{SIRM} + \text{IRM}_{-0.3\text{ T}})$. Second, medium-coercivity fraction of IRM (MIRM) was defined as $\text{MIRM} = 0.5 (\text{SIRM} + \text{IRM}_{-0.1\text{ T}}) - \text{HIRM}$.

On completion of all the field-treated experiments, representative cubes were dismantled for further analysis. Magnetic particles were separated using a hand magnet. Half of the extracted magnetic particles were examined under the microscope. Plastered caps were employed for the remaining half of the extracted magnetic particles. These caps were then one-inch cut for thermal treatment. At last, stepwise thermal demagnetization of 3-axis IRM (Lowrie 1990) was applied to the representative samples on the basis of their IRM behavior. IRMs were sequentially produced along the three mutually perpendicular directions using an ASC-Scientific IM-10-30 impulse magnetizer. Sequential fields used to produce a composite IRM were 1.2 , 0.4 , and 0.12 T along z -axis, x -axis, and y -axis, respectively.

Statistical analysis

Relationship between magnetic parameters in the topsoil was studied by means of Pearson correlation analyses. The Pearson correlation coefficient (R) was used to quantify the degree of linear relation in a bivariate system (Table 2).

Table 2 also lists correlation coefficient of determination (R^2) between pairs of twelve rock magnetic factors including χ_{fd} , χ_{ARM} , MAF, B_{cr} , forward S ratio at 0.1 T ($S_{0.1\text{ T}}$), backward S ratio at -0.1 T ($S_{-0.1\text{ T}}$) and at -0.3 T ($S_{-0.3\text{ T}}$), HIRM, MIRM, MDF, crossover field (B_{R}), and crossover point (P). Although crossover point has been abbreviated as R in rock magnetism and environmental magnetism communities, we used P to avoid confusion with the Pearson correlation coefficient (R).

Results

Spatial distribution of magnetic susceptibility

The magnetic susceptibility values ranged from 8.6 to $71.7 \times 10^{-5}\text{ SI}$ in the soils of profile S1 (Fig. 2). The mean and median magnetic susceptibility of S1 were $29.2 \pm 13.1 \times 10^{-5}\text{ SI}$ and $28.6 \times 10^{-5}\text{ SI}$, respectively. Two highest peaks occurred at 11.6 and 14.5 m away from the street (Fig. 2). Magnetic susceptibility of profiles S2 decayed to lower value from 0 to 55 m towards the south and then slightly enhanced from 55 to 100 m (Fig. 2). The mean and median magnetic susceptibility of S2 were $25.4 \pm 8.6 \times 10^{-5}\text{ SI}$ and $21.4 \times 10^{-5}\text{ SI}$, respectively. The profile S3 showed a peak at 62.5 m towards the south (Fig. 2). The mean and median magnetic susceptibility of S3 were $25.2 \pm 10.4 \times 10^{-5}\text{ SI}$ and $19.5 \times 10^{-5}\text{ SI}$, respectively. The coefficient of variation (CV) or relative standard deviation (RSD) is a percentage ratio of the standard deviation to the mean. The CV or RSD for S1, S2, S3 were 45.0 , 33.7 , 41.4% , respectively.

Three profiles towards the North appeared to be fairly similar with one another (Fig. 2). They all showed decreasing trend of magnetic susceptibility from 0 to 55 m , and then jumped to higher values (Fig. 2). The magnetic susceptibility values ranged from 13.2 to $53.5 \times 10^{-5}\text{ SI}$ in the soils of profile N1 (Fig. 2). The mean and median magnetic susceptibility were $29.9 \pm 9.6 \times 10^{-5}\text{ SI}$ and $29.0 \times 10^{-5}\text{ SI}$ for N1, $27.1 \pm 9.8 \times 10^{-5}\text{ SI}$ and $25.2 \times 10^{-5}\text{ SI}$ for N2, and $30.2 \pm 8.1 \times 10^{-5}\text{ SI}$ and $28.3 \times 10^{-5}\text{ SI}$ for N3, respectively. The CV or RSD for N1, N2, N3 were 31.9 , 36.2 , 26.7% , respectively. Values of CV or RSD were smaller for northern profiles than those for southern profiles, as the variation of magnetic susceptibility was more substantial in southern profiles (Fig. 2).

On the basis of magnetic susceptibility collected from six profiles, two dimensional map of magnetic susceptibility was constructed (Fig. 3). We found that the 5 and 95% percentile of magnetic susceptibility from a total of 238 readings were $10 \times 10^{-5}\text{ SI}$ and $50 \times 10^{-5}\text{ SI}$, respectively. Hence, these values were used as the lower and upper bound of 20 -step contours (Fig. 3). A contour map was produced from Grapher 10.5 with the lowest available data smoothing (i.e., smoothing factor = 1). It is evident that high values of magnetic susceptibility were narrowly concentrated adjacent to the street (Fig. 3). Magnetic susceptibility decreased away from the street to 55 m distance (Fig. 3). Magnetic susceptibility began to increase again, reaching 30 to $40 \times 10^{-5}\text{ SI}$ in southern profiles and 30 to $50 \times 10^{-5}\text{ SI}$ in northern profiles (Fig. 3).

Table 2 Pearson correlation coefficients between magnetic parameters ($N=26$)

Factors	χ_{fd}	χ_{ARM}	MAF	B_{cr}	$S_{0.1\text{ T}}$	$S_{-0.1\text{ T}}$	$S_{-0.3\text{ T}}$	HIRM	MIRM	MDF	B_R	P
χ_{fd}		$R = -0.57$	0.20	-0.09	-0.27	-0.06	-0.12	-0.12	0.09	0.08	0.10	0.11
		$R^2=0.33$	0.04	0.01	0.08	<0.01	0.01	0.01	0.01	0.01	0.01	0.01
		$p<0.01$	0.32	0.66	0.17	0.76	0.56	0.56	0.66	0.69	0.63	0.59
χ_{ARM}			-0.38	-0.28	0.43	0.17	-0.13	0.29	-0.24	-0.21	-0.35	-0.18
			0.15	0.08	0.18	0.03	0.02	0.09	0.06	0.04	0.12	0.03
			0.05	0.17	0.03	0.39	0.51	0.15	0.24	0.30	0.08	0.38
MAF				0.58	-0.86	-0.66	-0.05	-0.20	0.64	0.39	0.62	0.03
				0.34	0.74	0.43	<0.01	0.04	0.41	0.15	0.38	<0.01
				<0.01	<0.01	<0.01	0.81	0.33	<0.01	0.05	<0.01	0.87
B_{cr}					-0.39	-0.79	0.17	-0.55	0.85	0.76	0.88	0.53
					0.15	0.62	0.03	0.30	0.72	0.57	0.77	0.28
					0.05	<0.01	0.39	<0.01	<0.01	<0.01	<0.01	<0.01
$S_{0.1\text{ T}}$						0.56	0.23	<0.01	-0.49	-0.28	-0.48	-0.04
						0.31	0.05	<0.01	0.24	0.08	0.23	<0.01
						<0.01	0.26	0.99	0.01	0.16	0.01	0.86
$S_{-0.1\text{ T}}$							0.19	0.28	-0.96	-0.67	-0.79	-0.41
							0.04	0.08	0.93	0.45	0.62	0.17
							0.36	0.17	<0.01	<0.01	<0.01	0.04
$S_{-0.3\text{ T}}$								-0.47	-0.04	0.36	0.26	0.42
								0.22	<0.01	0.13	0.07	0.17
								0.02	0.86	0.07	0.20	0.03
HIRM									-0.53	-0.49	-0.51	-0.54
									0.28	0.24	0.26	0.29
									<0.01	0.01	<0.01	<0.01
MIRM										0.73	0.84	0.51
										0.53	0.71	0.26
										<0.01	<0.01	<0.01
MDF											0.93	0.87
											0.86	0.75
											<0.01	<0.01
B_R												0.72
												0.52
												<0.01
P												

χ_{fd} (%) = $[(\chi_{lf} - \chi_{hf})/\chi_{lf}] \times 100$; χ_{ARM} susceptibility of anhysteretic remanent magnetization; MAF median acquisition field; B_{cr} coercivity of remanence; $S_{0.1\text{ T}} = \text{IRM}_{0.1\text{ T}}/\text{SIRM}$; $S_{-0.1\text{ T}} = 0.5 (1 - \text{IRM}_{-0.1\text{ T}}/\text{SIRM})$; $S_{-0.3\text{ T}} = 0.5 (1 - \text{IRM}_{-0.3\text{ T}}/\text{SIRM})$; $\text{HIRM} = 0.5 (\text{SIRM} + \text{IRM}_{-0.3\text{ T}})$; $\text{MIRM} = 0.5 (\text{SIRM} + \text{IRM}_{-0.1\text{ T}}) - \text{HIRM}$; MDF median destructive field; B_R Crossover field; P Crossover point; R Pearson correlation coefficient; R^2 correlation coefficient of determination; p : significance level (in bold)

Grain proxy

The mean of χ_{fd} was $2.21 \pm 1.27\%$, with only four samples exceeding 4% (Table 1). The low χ_{fd} values (<5%) indicate that SP grains do not exist in considerable amounts in the topsoil of studied samples (e.g., Dearing et al. 1996; Magiera et al. 2011, 2013). Such low χ_{fd} was the characteristics of roadside dusts (e.g., Shilton et al. 2005; Yang et al.

2010; Bourliva et al. 2016). χ_{fd} and χ_{lf} were approximately inversely correlated (Fig. 4a), consistent with the frequency dependence of magnetic susceptibility observed for ferri-magnetic grains (Dearing et al. 1996).

Plots of χ_{ARM} versus χ_{lf} (Fig. 4b) were useful to detect changes in the relative grain-size of ferrimagnetic grains in natural materials (King et al. 1982). Observed data fell in the range of 0.1–20 μm magnetite particles (Fig. 4b).

Fig. 2 Profiles of soil-surface magnetic susceptibility. A total of 238 readings were taken (40 from S1, 31 from S2, 32 from S3, 40 from N1, 54 from N2, 41 from N3)

Fig. 3 Contour plot of magnetic susceptibility values in the topsoil. Elevation (i.e., depth) profile along the transect was provided as an inset

Fig. 4 **a** Plots of χ_{fd} percentage versus χ_{lf} . **b** Bivariate plot of χ_{AMS} versus χ_{lf} . Reference lines were retrieved from King et al. (1982)

Fig. 5 **a** Normalized curves for the acquisition of IRM. **b** Back-field decay of saturation IRM

Isothermal remanent magnetization

The IRM acquisition curves (Fig. 5) were rapidly increasing at low fields (< 100 mT). They reached saturation by 300 mT, indicating a predominance of low-coercivity Fe-oxides (Fig. 5a). The median acquisition field (MAF) was defined as the impulse field that reached the 50% of SIRM. Values of MAF varied from 33.7 mT (GCD31) to 98.9 mT (GCB29), with a mean of 56.2 ± 14.2 mT (Table 1).

The coercivity of remanence (B_{cr}) was determined from the back-field IRM curves (Fig. 5b). Values of B_{cr} varied from 23.7 mT (GCD40) to 60.1 mT (GCB11), with a mean of 33.9 ± 7.5 mT (Table 1). Values of $S_{-0.1T}$ ranged from 0.683 (GCB11) to 0.896 (GCE30), with a mean of 0.823 ± 0.049 (Table 1). Values of $S_{-0.3T}$ were larger than those of $S_{-0.1T}$, with a mean of 0.961 ± 0.011 (Table 1). The HIRM reflects the amount of hard magnetic phase (hematite

or goethite) in mineral mixtures that also contain magnetite (Liu et al. 2007). High S -ratios ($S_{-0.1T}$ and $S_{-0.3T}$) and low HIRM indicate a prominence of low-coercivity magnetic particulates (Table 1). The MIRM reflects the amount of medium-coercivity magnetic phase in mineral mixtures. The MIRM varied from 0.087 (GCE30) to 0.306 (GCB11), with a mean of 0.147 ± 0.055 (Table 1).

The median destructive field (MDF) was defined as the AF that reduced the NRM by 50% (Fig. 6a, Table 1). The MDF thus reflects the coercivity spectra of magnetic particles. Values of MDF ranged from 5.4 mT (GCF15) to 45.2 mT (GCB11), with a mean of 13.7 ± 7.9 mT (Table 1). Intersection point between IRM acquisition and IRM decay curves lied well below 0.5, indicating some degree of grain interaction (Table 1).

One set of coercivity spectra (M_{AF}) were constructed from stepwise AF demagnetization of SIRM. Another

Fig. 6 Composite diagrams showing **a** AF demagnetization of saturation IRM, **b** difference between normalized AF demagnetization curves between observed M_{BF} and synthesized M_{BF}^* . Back-field coer-

civity spectra were constructed from AF demagnetization of SIRM (M_{AF}) with a relation of $M_{BF}^* = 1 - 2M_{AF}$

independent set of coercivity spectra (M_{BF}) can be obtained during back-field IRM decay curves. According to Wohlfarth theory (Wohlfarth 1958), non-interacting single domain (SD) particles satisfy the relation of $M_{BF}^* = 1 - 2 M_{AF}$. When M_{BF} was plotted against M_{AF} , ideal non-interacting SD grains would yield a slope of -2 with a y-intercept at $+1$ (Henkel 1964). In reality, observed M_{BF} and synthesized M_{BF}^* from M_{AF} would be different unless samples are free of interaction. The difference between observed M_{BF} and synthesized M_{BF}^* was represented as ΔM (e.g., Mayo et al. 1990, 1991a, b; Speliotis and Lynch 1991). It is common to observe negative ΔM in most field intervals as interaction tends to lower magnetization (Petrovský et al. 1993). Although rare, positive ΔM is possible in some field intervals, where positive interaction induces enhanced magnetization. In the present study, we found negative ΔM from all samples (Fig. 6b). It should be noted that sample GCB29 showed the deepest negative ΔM and the largest MAF, indicative of strongly interacting fine-grained magnetic particles in this sample (Fig. 6b, Table 1).

The maximum unblocking temperatures of composite IRMs (Lowrie 1990) were 580 °C which is the Curie temperature of magnetite, suggesting that the magnetic mineralogy was dominated by magnetite (Fig. 7a). Under the microscope, we found two different types of magnetic material. About two thirds of magnetic particles were angular in

shape, with various sizes from 20 to 400 μm (Fig. 7b). The presence of lithogenic magnetite is clearly shown by angular magnetite with octahedral morphology (Fig. 7b). Other particles showed spherical morphologies with relative uniform diameters of about 50 μm or less (Fig. 7b).

Discussion

Spatial distribution of magnetic susceptibility

A generally higher level of magnetic susceptibility was observed near the roadside base of profiles (Figs. 2 and 3). Compared to the peripheries of the studied area, magnetic susceptibilities were much more pronounced getting closer to the main street. It is natural to anticipate that magnetic susceptibility decreases with distance from the input source (e.g., Hoffmann et al. 1999). The highest magnetic susceptibility was observed within a distance of a few meters from the main street. Such characteristics can be related to the emission of the traffic pollution produced by vehicular engine emissions (e.g., Zechmeister et al. 2005; Bućko et al. 2010; Werkenthin et al. 2014; Wawer et al. 2015; Ma et al. 2016; Nikolaeva et al. 2017; Pierwola et al. 2020). Magnetic enhancement getting closer to the main street decayed exponentially from 0 to 55 m with respect to the distance (Figs. 2 and 3) due to magnetic grain size or the amount of magnetic particles with distances away from the source.

In the present study, magnetic susceptibility was lower away from the road, because air circulation was intense along the river, less efficient in settling of magnetic particles on the grassland. The lowest values of magnetic susceptibility occurred about 55 m away from the main street and a systematic increase of susceptibility towards the roads was observed (Fig. 2). Perhaps, the air flow became less significant to settle magnetic particles with increasing distance from the road. It should be noted that magnetic susceptibility enhanced again from 55 to 100 m to form local magnetic highs around the periphery (Figs. 2 and 3). The localized, narrow and linear anomalies represent enhancement of magnetic susceptibility parallel to the street alignment, typical characteristics of traffic-related particles (Hoffmann et al. 1999; Zechmeister et al. 2005; Bućko et al. 2010; Werkenthin et al. 2014; Ma et al. 2016; Nikolaeva et al. 2017; Pierwola et al. 2020).

A few magnetic hotspots around the periphery with intensities of magnetic susceptibility near or over 50×10^{-5} SI might represent the possible input of magnetic material from the nearby alleys if we stick only to the traffic sources (Figs. 2 and 3). However, more realistic explanation would be the difference in topographic elevation and surface morphology. Indeed, local magnetic highs are located in lower

Fig. 7 **a** Thermal demagnetization curves of a three-component (hard, medium, soft) IRM (Lowrie 1990), indicating a presence of magnetite. **b** Representative images of spherical and angular magnetic particulates

elevation, where decline trend of elevation stops (Fig. 3). It is possible that magnetic particles were continuously accumulated in these low elevations over time.

In nature, anthropogenic pollutants occurred in solid, liquid, and gas phases or a combination of multiple phases. Because of on-going water cycling events (i.e., rain or snow), fluidal phases of pollutants were washed away and/or penetrated into the ground. As a result, only the solid phase will dominate the magnetic signal in the topsoil. The solid phase may include pollutants produced mostly by abrasion and corrosion. On the basis of crystal morphology, it is likely that angular iron-rich oxide particles were possibly originated from traffic-related process or natural source (Fig. 7b). It was well documented that vehicles produce angular magnetite particles via non-exhaust emissions as a result of abrasion of brake linings, as well as the abrasion or corrosion of vehicle engine and body work (e.g., Matzka and Maher 1999; Bućko et al. 2010; Bourliva et al. 2016). Particles in rounded shapes were unlikely to represent natural minerals, but were produced by fossil fuel combustion process considering their morphological characteristics (Fig. 7b). Iron-oxide spherules are definitely high-temperature origin, characteristic of vehicle exhaust emission or fly ash particles derived from fossil fuel combustion process (e.g., Spiteri et al. 2005; Goodarzi 2006; Jordanova et al. 2008). These pollutants are probably transported from western coastal industrial areas of South Korea and eastern coastal industrial areas of China (e.g., Kim et al. 2012; Baatar et al. 2017; Ha et al. 2017).

Magnetic minerals are inherited from the parent materials of soils throughout the process of weathering and pedogenesis. Urbanization process accompanies steady accumulation of heavy metals in association with magnetic particles to the soils (Karimi et al. 2011; Dankoub et al. 2012). Influence of pedogenic production of secondary ferrimagnetic material also needs to be counted. Considering meteorological data (e.g., annual rainfalls) and topographic information (e.g., elevation difference), pedogenesis was possibly disturbed continuously under pasture. It should be noted that pedogenic particles are usually much smaller than angular magnetites observed in the present study (Fig. 7b), and usually regular in shape, because they were formed in natural conditions (e.g., Bućko et al. 2010, 2011; Bourliva et al. 2016, 2018). Hence, pedogenic production of secondary ferrimagnetic material was probably insignificant, although we cannot completely rule out the possibility.

Rock magnetic characteristics

Because weak-field properties (e.g., χ_{ARM} and χ_{fd}) are sensitive to fine-grained ferrimagnetic particles, they have been

commonly used as granulometric indicators in rock magnetism and environmental magnetism. χ_{fd} did not show any significant correlation with IRM-related parameters (Fig. 4), simply because our soil samples were virtually devoid of SP grains (Table 2). Similarly, χ_{ARM} lacked correlation with IRM-related parameters, also supporting near absence of extremely fine particles (Table 2). Hence, we will focus only on the mutual correlation between high-field IRM-relevant parameters.

S-ratios represent the fraction of lower coercivity minerals to higher coercivity minerals (e.g., Salomé and Meynadier 2004; Liu et al. 2007). Values of $S_{0.1\text{ T}}$, $S_{-0.1\text{ T}}$, and $S_{-0.3\text{ T}}$ ranged from 0.502 to 0.834, 0.683 to 0.896, and 0.938 to 0.991, respectively (Table 1). In particular, values of $S_{-0.3\text{ T}}$ were extremely high, indicative of a low content of high coercivity minerals. This agrees well with the fact that the IRM acquisitions were saturated by 0.3 T in all samples (Fig. 5).

A total of 25 pairs out of 66 possible combinations yielded significant results with $p < 0.01$ (Table 2). Among ten rock magnetic factors used, B_{cr} was chosen as the common parameters in all correlation diagrams (Fig. 8). It is evident that B_{cr} showed significant correlation with seven other factors (Table 2). For instance, there is a correlation between MDF and B_{cr} ($R^2 = 0.5711$, Fig. 8a), B_{R} and B_{cr} ($R^2 = 0.7711$, Fig. 8b), MIRM and B_{cr} ($R^2 = 0.7223$, Fig. 8c), P and B_{cr} ($R^2 = 0.2809$, Fig. 8d), and $S_{-0.1\text{ T}}$ and B_{cr} ($R^2 = 0.6164$, Fig. 8e). As the values of R^2 were relatively smaller, it must be regarded that MDF (Fig. 8a) and P (Fig. 8d) as less diagnostic to B_{cr} than other parameters of B_{R} , MIRM, or $S_{-0.1\text{ T}}$. No significant correlation between $S_{-0.3\text{ T}}$ and B_{cr} ($R^2 = 0.0303$, Fig. 8f) was observed. It is apparent that $S_{-0.3\text{ T}}$ is not correlated with all other factors, simply because $S_{-0.3\text{ T}}$ was too high to show any significant trend (Table 2). Insensitivity of $S_{-0.3\text{ T}}$ in this study was somewhat anticipated as high coercivity material is nearly absent in our soil samples (Table 1).

The classical rock magnetic approach requires modification to incorporate more objective IRM unmixing analysis developed by Kruiver and Passier (2001). We applied the MaxUnMix (Maxbauer et al. 2016, 2017), which is an upgraded semi-automated version of the IRM unmixing analysis (Kruiver and Passier 2001). IRM component analysis yielded one or two magnetic components (Fig. 9). For example, sample GCD31 had 63.0% of softer component (21.3 mT) and 37.0% of harder component (81.3 mT) (Fig. 9a). Results from GCD40 (Fig. 9b) were similar to those of GCD31. Nearly equal contribution from softer component and harder component was observed for GCA05 (Fig. 9c), GCB18 (Fig. 9d), and GCB29 (Fig. 9e). In these samples, dual coercivity peaks were more prominent (Fig. 9c–e) than those for GCD31 or

Fig. 8 Relation between various magnetic parameters including **a** median destructive field (MDF) and coercivity of remanence (B_{cr}), **b** crossover field (B_R) and B_{cr} , **c** MIRM and B_{cr} , **d** crossover point (P) and B_{cr} , **e** $S_{-0.1 T}$ and B_{cr} , and **f** $S_{-0.3 T}$ and B_{cr}

GCD40. Of course, distributions of dual coercivity components were not clearly separable as to blur overlapped coercivity intervals (Fig. 9a–e). Results from GCB11 (Fig. 9f) deserved special attention, because it showed the largest B_{cr} values (Fig. 8). There was only a single component for GCB11 whose mean coercivity was peaked at 90.7 mT (Fig. 9f).

What controls the magnetic coercivity spectra in the soil samples? Results from MaxUnMix are well-explained with two distributions of low coercivity phase (21.3–36.4 mT) and high coercivity phase (81.3–151.1 mT). Exceptional results for GCB11 can be regarded as a single coercivity distribution of entirely high-coercivity phase (Fig. 9f). However, a linkage between classical IRM-related parameters (Figs. 5, 6, 7 and 8) and IRM component analysis using MaxUnMix (Fig. 9) was far from being a simple linear relation. The bulk of the observations are consistent with the notion that both classical IRM-related parameters (i.e., S ratios) and IRM component analysis using MaxUnMix are imperfect as a fine probe of granulometry. As the thermal demagnetization of composite IRM data yielded magnetite as the sole remanence carrier (Fig. 7a), it is possible that particle size distribution induced dual coercivity distribution

in the soils samples. To this end, it is likely that the softer component was dominated by a lower coercivity component which is interpreted to be angular magnetite originated from exhaust emissions. On the other hand, the harder component was dominated by a high coercivity component that is fine-grained spherical magnetite resulted from fossil fuel combustion process.

Conclusions

Two dimensional map of magnetic susceptibility was constructed using the magnetic susceptibility data measured on 238 topsoil samples from six profiles in Daejeon, South Korea. High values of magnetic susceptibility were narrowly concentrated adjacent to the street. Magnetic susceptibility decreased away from the street. Presence of magnetic hotspots around the periphery with intensities of magnetic susceptibility near or over 50×10^{-5} SI might represent the difference in topographic elevation and surface morphology, because magnetic particles were continuously accumulated in low elevations over time. The maximum unblocking temperatures of composite IRMs were 580 °C, suggesting that

Fig. 9 Coercivity spectra of **a** GCD31, **b** GCD40, **c** GCA05, **d** GCB18, **e** GCB29, and **f** GCB11 determined from MaxUnMix software package (Maxbauer et al. 2016, 2017)

the magnetic mineralogy was dominated by magnetite. IRM component analysis showed dual coercivity peaks in most samples. It is likely that the softer component was dominated by coarse-grained angular magnetite originated from vehicle non-exhaust emissions. On the other hand, the harder component was dominated by fine-grained spherical magnetite resulted from exhaust emissions.

Acknowledgements The authors declare that they have no competing financial interests. All the data used for this study were tabulated in the Supplementary Excel file. We thank Nawrass Ameen and two anonymous referees for helpful reviews that greatly improved the paper. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NRF-2018R1A2B6001094) and by the Korea Foundation for the Advancement of Science & Creativity (KOFAC), and funded by the Korean Government (MOE).

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will

need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ayoubi S, Adman V (2019) Iron mineralogy and magnetic susceptibility of soils developed on various rocks in western Iran. *Clays Clay Miner* 67:217–227
- Ayoubi S, Karimi R (2019) Pedotransfer functions for predicting heavy metals in natural soils using magnetic measures and soil properties. *J Geochem Explor* 197:212–219
- Ayoubi S, Adman V, Yousefifard M (2019a) Efficacy of magnetic susceptibility technique to estimate metal concentration in some igneous rocks. *Model Earth Syst Environ* 5:1743–1750
- Ayoubi S, Adman V, Yousefifard M (2019b) Use of magnetic susceptibility to assess metals concentration in soils developed on a range of parent materials. *Ecotox Environ Safety* 168:138–145
- Baatar A, Ha R, Yu Y (2017) Do rainfalls wash out anthropogenic airborne magnetic particulates? *Environ Sci Pollut Res* 24:9713–9722
- Blaha U, Appel E, Stanjek H (2008) Determination of anthropogenic boundary depth in industrially polluted soil and semi-quantification of heavy metal loads using magnetic susceptibility. *Environ Pollut* 156:278–289
- Bloemendal J, King JW, Hall FR, Doh SJ (1992) Rock magnetism of Late Neogene and Pleistocene deep-sea sediments: relationship to sediment source, diagenetic processes and sediment lithology. *J Geophys Res* 97:4361–4375

- Bourliva A, Papadopoulou L, Aidona E (2016) Study of road dust magnetic phases as the main carrier of potentially harmful trace elements. *Sci Total Environ* 553:380–391
- Bourliva A, Kantiranis N, Papadopoulou L, Aidona E, Christophoridis C, Kollias P, Evgenakis M, Fytianos L (2018) Seasonal and spatial variations of magnetic susceptibility and potentially toxic elements (PTEs) in road dusts of Thessaloniki city, Greece: A one-year monitoring period. *Sci Total Environ* 639:417–427
- Boyko T, Scholger R, Stanjek H, MAGPROX Team (2004) Topsoil magnetic susceptibility mapping as a tool for pollution monitoring: repeatability of in situ measurements. *J Appl Geophys* 55:249–259
- Bučko MS, Magiera T, Pesonen LJ, Janus B (2010) Magnetic, geochemical, and microstructural characteristics of road dust on roadsides with different traffic volumes—case study from Finland. *Water Air Soil Pollut* 209:295–306
- Bučko MS, Magiera T, Johanson B, Petrovský E, Pesonen LJ (2011) Identification of magnetic particulates in road dust accumulated on roadside snow using magnetic, geochemical and micro-morphological analyses. *Environ Pollut* 159:1266–1276
- Chaparro MAE, Bidegain JC, Sinito AM, Jurado SS, Gogorza CG (2004) Magnetic studies applied to different environments (soils and stream sediments) from a relatively polluted area in Buenos Aires Province, Argentina. *Environ Geol* 45:654–664
- Dankoub Z, Ayoubi S, Khademi S, Lu SG (2012) Spatial distribution of magnetic properties and selected heavy metals in calcareous soils as affected by land use in the Isfahan region, Central Iran. *Pedosphere* 22:33–47
- Dearing JA, Dann RJA, Hay K, Lees JA, Loveland PJ, Maher BA, O'Grady K (1996) Frequency-dependent susceptibility measurements of environmental materials. *Geophys J Int* 124:228–240
- Dong C, Zhang W, Ma H, Feng H, Luc H, Dong Y, Yua L (2014) A magnetic record of heavy metal pollution in the Yangtze River subaqueous delta. *Sci Total Environ* 476–477:368–377
- El-Hasan T (2008) The detection of roadside pollution of rapidly growing city in arid region using the magnetic proxies. *Environ Geol* 54:23–29
- Evans ME, Heller F (2003) Environmental magnetism: principles and applications of enviromagnetics. Academic Press, San Diego, p 311
- Gautam P, Blaha U, Appel E, Neupane G (2004) Environmental magnetic approach towards the quantification of pollution in Kathmandu urban area. *Nepal Phys Chem Earth* 29:973–984
- Goodarzi F (2006) Characteristics and composition of fly ash from Canadian coal-fired power plants. *Fuel* 85:1418–1427
- Grison H, Petrovský E, Stejskalova S, Kapička, (2015) Magnetic and geochemical characterization of Andosols developed on basalts in the Massif Central. France *Geochem Geophys Geosyst* 16(5):1348–1363
- Ha R, Baatar A, Yu Y (2017) Identification of atmospheric transport and dispersion of Asian dust storms. *Nat Hazards Earth Syst Sci* 17:1425–1435
- Hanesch M, Scholger R (2002) Mapping of heavy metal loadings in soils by means of magnetic susceptibility measurements. *Environ Geol* 42:857–870
- Hanesch M, Scholger R, Rey D (2003) Mapping dust distribution around an industrial site by measuring magnetic parameters of tree leaves. *Atmos Environ* 37:5125–5133
- Hanesch M, Rantitsch G, Hemetsberger S, Scholger R (2007) Lithological and pedological influences on the magnetic susceptibility of soil: Their consideration in magnetic pollution mapping. *Sci Total Environ* 382:351–363
- Henkel O (1964) Remanenzverhalten und wechselwirkungen in hartmagnetischen teilchenkollektiven. *Phys Status Solidi (b)* 161:K41–K44 (in German)
- Heslop D (2009) On the statistical analysis of the rock magnetic S-ratio. *Geophys J Int* 178:159–161
- Hoffmann V, Knab M, Appel E (1999) Magnetic susceptibility mapping of roadside pollution. *J Geochem Explor* 66:313–326
- Hwang J, Moon S (2018) Geochemical evidence for K-metasomatism related to uranium enrichment in Daejeon granitic rocks near the central Ogcheon Metamorphic Belt, Korea. *Geosci J* 22:1001–1013
- Jelenska M, Hasso-Agopsowicz A, Kopcewicz B, Sukhorada A, Tyamina K, Kadzialko-Hofmoki M, Matviishina Z (2004) Magnetic properties of the profile of polluted and non-polluted soils: a case study from Ukraine. *Geophys J Int* 159:104–116
- Jordanova N, Jordanova D, Henry B, Le Goff M, Dimov D, Tsacheva T (2006) Magnetism of cigarette ashes. *J Mag Mag Mater* 301:50–66
- Jordanova N, Jordanova D, Tsacheva T (2008) Application of magnetometry for delineation of anthropogenic pollution in areas covered by various soil types. *Geoderma* 144:557–571
- Jordanova D, Goddu SR, Kotsev T, Jordanova N (2013) Industrial contamination of alluvial soils near Fe–Pb mining site revealed by 441 magnetic and geochemical studies. *Geoderma* 192:237–248
- Karimi R, Ayoubi S, Jalalian A, Sheikh-Hosseini AR, Afyuni M (2011) Relationships between magnetic susceptibility and heavy metals in urban topsoils in the arid region of Isfahan, central Iran. *J Appl Geophys* 74:1–7
- Karimi R, Haghnia GH, Ayoubi S, Safari T (2017) Impacts of geology and land use on magnetic susceptibility and selected heavy metals in surface soils of Mashhad plain, northeastern Iran. *J Appl Geophys* 128:127–134
- Kim W, Doh SJ, Park YH (2007) Two-year magnetic monitoring in conjunction with geochemical and electron microscopic data of roadside dust in Seoul, Korea. *Atmos Environ* 41:7627–7641
- Kim W, Doh SJ, Yu Y (2012) Asian dust storm as conveyance media of anthropogenic pollutants. *Atmos Environ* 49:41–50
- King J, Banerjee SK, Marvin J, Özdemir Ö (1982) A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: Some results from lake sediments. *Earth Planet Sci Lett* 59:404–419
- Kruiver PP, Passier HF (2001) Coercivity analysis of magnetic phases in sapropel S1 related to variations in redox conditions, including an investigation of the S-ratio. *Geochem Geophys Geosyst* 2(12):1063. <https://doi.org/10.1029/2001GC000181>
- Liu QS, Roberts AP, Torrent J, Horng CS, Larrasoña JC (2007) What do the HIRM and S-ratio really measure in environmental magnetism? *Geochem Geophys Geosyst* 8:Q09011. <https://doi.org/10.1029/2007GC001717>
- Liu QS, Roberts AP, Larrasoña JC, Banerjee SK, Guyodo Y, Tauxe L, Oldfield F (2012) Environmental magnetism: principles and applications. *Rev Geophys* 50:1–50
- Lowrie W (1990) Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophys Res Lett* 17:159–162
- Lu SG, Bai SQ (2006) Study on the correlation of magnetic properties and heavy metals content in urban soils of Hangzhou City, China. *J Appl Geophys* 60:1–12
- Lu SG, Bai SQ, Xue QF (2007) Magnetic properties as indicators of heavy metal pollution in urban topsoils: a case study from the city of Luoyang, China. *Geophys J Int* 171:568–580
- Lu SG, Wang HY, Guo JL (2011) Magnetic enhancement of urban roadside soils as a proxy. *Environ Earth Sci* 64:359–371
- Ma M, Hu S, Wang L, Appel E (2016) The distribution process of traffic contamination on roadside surface and the influence of meteorological conditions revealed by magnetic monitoring. *Environ Monitor Assess* 188:650. <https://doi.org/10.1007/s10661-016-5661-0>

- Magiera T, Jabłońska M, Strzyszczyński Z, Rachwał M (2011) Morphological and mineralogical forms of technogenic magnetic particles in industrial dusts. *Atmos Environ* 45:4281–4290
- Magiera T, Goluchowska B, Jabłońska M (2013) Technogenic magnetic particles in alkaline dusts from power and cement plants. *Water Air Soil Pollut* 224:1389–1405
- Maher BA, Moore C, Matzka J (2008) Spatial variation in vehicle derived metal pollution identified by magnetic and elemental analysis of roadside tree leaves. *Atmos Environ* 42:364–373
- Matzka J, Maher BA (1999) Magnetic biomonitoring of roadside tree leaves: identification of spatial and temporal variations in vehicle-derived particulates. *Atmos Environ* 33:4565–4569
- Maxbauer DP, Feinberg JM, Fox DL (2016) MaxUnMix: A web application for unmixing magnetic coercivity distributions. *Comp Geosci* 95:140–145
- Maxbauer DP, Feinberg JM, Fox DL, Nater E (2017) Response of pedogenic magnetite to changing vegetation in soils developed under uniform climate, topography, and parent material. *Sci Reports* 7:17575. <https://doi.org/10.1038/s41598-017-17722-2>
- Mayo PI, Erkkila RM, Bradbury A, Chantrell RW (1990) Interaction effects in longitudinally oriented and non-oriented barium hexaferrite tapes. *IEEE Trans Mag* 26(5):1894–1896
- Mayo PI, O'Grady K, Chantrell RW, Cambridge JA, Sanders IL, Yogi T, Howard JK (1991a) Magnetic measurement of interaction effects in CoNiCr and CoPtCr thin film media. *J Mag Mater* 95(1):109–117
- Mayo PI, O'Grady K, Kelly PE, Cambridge J, Sanders IL, Yogi T, Chantrell RW (1991b) A magnetic evaluation of interaction and noise characteristics of CoNiCr thin films. *J Appl Phys* 69(8):4733–4735
- Muxworthy AR, Matzka J, Petersen N (2001) Comparison of magnetic parameters of urban atmospheric particulate matter with pollution and meteorological data. *Atmos Environ* 35:4379–4386
- Nikolaeva O, Rozanova M, Karpukhin M (2017) Distribution of traffic-related contaminants in urban topsoils across a highway in Moscow. *J Soils Sediments* 17:1045–1053
- Ojha G, Appel E, Wawer M, Magiera T, Hu S (2016) Toward a cost-efficient method for monitoring of traffic-derived pollutants with quartz sand boxes. *Water Air Soil Pollut* 227:173. <https://doi.org/10.1007/s11270-016-2858-3>
- Petrovský E, Hejda P, Zelinka T, Kropáček V, Šubrt J (1993) Experimental determination of magnetic interaction within a system of synthetic hematite particles. *Phys Earth Planet Inter* 76(1–2):123–130
- Petrovský E, Kapička A, Jordanova N, Knab M, Hoffmann V (2000) Low-field magnetic susceptibility: a proxy method of estimating increased pollution of different environmental systems. *Environ Geol* 39:312–318
- Pierwola J, Szuszkiewicz M, Cabala J, Jochymczyk K, Żogała B, Magiera T (2020) Integrated geophysical and geochemical methods applied for recognition of acid waste drainage (AWD) from Zn-Pb post-flotation tailing pile (Olkusz, southern Poland). *Environ Sci Pollut Res* 27:16731–16744
- Prajapati SK, Pandey SK, Tripathi BD (2006) Monitoring of vehicles derived particulates using magnetic properties of leaves. *Environ Monitor Assess* 120:169–175
- Salomé AL, Meynadier L (2004) Magnetic properties of river sands and rocks from Martinique Island: tracers of weathering? *Phys Chem Earth* 29(3–4):933–945
- Schmidt A, Yarnold R, Hill M, Ashmore M (2005) Magnetic susceptibility as proxy for heavy metal pollution: a site study. *J Geochem Explor* 85:109–117
- Shilton VF, Booth CA, Smith JP, Giess P, Mitchell DJ, Williams CD (2005) Magnetic properties of urban street dust and their relationship with organic matter content in the West Midlands, UK. *Atmos Environ* 39:3651–3659
- Spiliotis DE, Lynch W (1991) Magnetic interaction in particulate and thin-film recording media. *J Appl Phys* 69(8):4496–4498
- Spiteri C, Kalinski V, Rosler W, Hoffmann V, Appel E, MAGPROX team (2005) Magnetic screening of a pollution hotspot in the Lausitz area, Eastern Germany: correlation analysis between magnetic proxies and heavy metal contamination in soils. *Environ Geol* 49:1–9
- Stober JC, Thompson R (1979) An investigation into the source of magnetic minerals in some Finnish lake sediments. *Earth Planet Sci Lett* 45:464–474
- Tolonen K, Oldfield F (1986) The record of magnetic-mineral and heavy metal deposition at Regent Street Bog, Fredericton, New Brunswick, Canada. *Phys Earth Planet Inter* 42:57–66
- Torrent J, Liu Q, Barrón V (2010) Magnetic susceptibility changes in relation to pedogenesis in a Xeralf chronosequence in northwestern Spain. *Eur J Soil Sci* 61:161–173
- Wawer M, Magiera T, Ojha G, Appel E, Kusza G, Hu S, Basavaiah B (2015) Traffic-related pollutants in roadside soils of different countries in Europe and Asia. *Water Air Soil Pollut*. <https://doi.org/10.1007/s11270-015-2483-6>
- Werkentin M, Kluge B, Wessolek G (2014) Metals in European roadside soils and soil solution—a review. *Environ Pollut* 189:98–110
- Wohlfarth EP (1958) Relations between different modes of the acquisition of the remanent magnetization of ferromagnetic particles. *J Appl Phys* 29:595–596
- Yamazaki T, Abdeldayem AL, Ikehara L (2003) Rock-magnetic changes with reduction diagenesis in Japan Sea sediments and preservation of geomagnetic secular variation in inclination. *Earth Planets Space* 55:327–340
- Yan HT, Hu SY, Blaha U, Rösler W, Duan XM, Appel E (2011) Paddy soil - A suitable target for monitoring heavy metal pollution by magnetic proxies. *J Appl Geophys* 75:211–219
- Yang T, Liu Q, Chan L, Liu Z (2007) Magnetic signature of heavy metals pollution of sediments: case study from the East Lake in Wuhan, China. *Environ Geol* 52:1639–1650
- Yang T, Liu Q, Zeng Q, Chan L (2009) Environmental magnetic responses of urbanization processes: evidence from lake sediments in East Lake, Wuhan. *China Geophys J Int* 179(2):873–886
- Yang T, Liu Q, Li H, Zeng Q, Chan L (2010) Anthropogenic magnetic particles and heavy metals in the road dust: magnetic identification and its implications. *Atmos Environ* 44:1175–1185
- Zechmeister HG, Hohenwallner D, Riss A, Hanus-Illy A (2005) Estimation of element deposition derived from road traffic sources by using mosses. *Environ Pollut* 138:238–249
- Zhang C, Qiao Q, Piper JDA, Huang B (2011) Assessment of heavy metal pollution from a Fe-smelting plant in urban river sediments using environmental magnetic and geochemical methods. *Environ Pollut* 159:3057–3070
- Zhu Z, Li Z, Bi X, Han Z, Yu G (2013) Response of magnetic properties to heavy metal pollution in dust from three industrial cities in China. *J Hazard Mater* 246–247:189–198

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.