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Magnetic response to atmospheric heavy metal pollution recorded by dust-loaded leaves in Shougang industrial area, western Beijing

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Fifty-five evergreen tree's leaves growing less than one year were collected from Shougang industrial area in western suburb of Beijing, including steel plants and its ambient residential areas, recreational parks and farmlands. Rock magnetic properties and heavy metal contents were studied. The results show that the magnetic properties of leaf samples are predominated by low-coercivity magnetite, and both the concentration and grain size of magnetite particles gradually decreased with the distance from the main pollution source increases. Moreover, there is a significant linear relationship between magnetic parameters (the low-field magnetic susceptibility, saturation isothermal remanent magnetization and anhysteretic remanent magnetization) and heavy metals contents (Fe, Pb, V, Cr and Zn) ($0.73\leqslant R\leqslant 0.88$). Hence, the magnetic parameters of leaves can serve as a proxy for quick detecting of the recent atmospheric metallic pollution.

Shougang industrial area, tree leaves, magnetic parameters, heavy metal contents

In the last few years, rapid development in industry has caused serious impacts to air quality due to the discharge of exhaust gases and dusts derived from combustion processes. Especially, atmospheric heavy metal pollution still is a major problem for the urban environment, as well as the economical and social development[1].The greatest health impacts may come from the fine-grain particulate material with sizes less than 10 μm, which can be inhaled deeply into the alveolar sections of the lungs, injuring the lung's function, and causing diseases, such as pneumonia of the respiratory system, even threatening human life[2]. Therefore, it is of significance both in science and in practice to learn and monitor air pollution in urban and industrial areas.

There are different objects and methods used for studying atmospheric heavy metal pollution. The use of high volume active air samplers equipped with filters is very common, yet expensive and time-consuming. Additionally, filters appear to be inefficient collectors for the smallest particles. Establishing a dense grid of atmospheric dust filters for particle investigations is a rather time consuming and costly work, and it is very difficult to apply on a large scale[3]. Collecting street dust is less expensive. Street dust, however, will likely contain larger particles, which is not airborne and poses little health risk[4−6]. Soils as a pollution receptor reflect

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a relatively long pollution history (accumulating within years, decades, and even longer time); in addition, the signal of the geological background is highly variable in a large areas and the urban soil is strongly influenced by anthropogenic input. All this creates difficulties in sampling. Thus, it is a challenge to select new scientific research targets, and to search for new working methods for investigating atmospheric heavy metals pollution efficiently and economically.

In the last few years, magnetic monitoring of tree leaves has been used as a target for studying air pollution, which is one of the new developments of environmental magnetism. Several magnetic studies on tree leaves[7−14] have shown that there is some certain correlation between regional air quality and magnetic properties of tree leaves along traffic lines and in industrial areas, and magnetic variation can reflect the changes of the current atmosphere quality. Thus, it can be taken as a proxy during pollution study. Leaves have many advantages in monitoring atmospheric heavy metal pollution. First, leaves have a large surface area per unit weight and a certain long lifespan. Its wax layer can directly absorb and keep dust, suspended particles and non-volatile organic compounds**.** Especially**,** it can easily capture the particulates less than 10 μm, which then can transfer to the inner layer from epidermis by diffusion; second, the magnetic particles absorbed from the roots and soils can be neglected compared to those come from leaf wax layers. So, the biological background of tree leaves is very low. Furthermore, leaves are widely distributed and available, and therefore, are convenient for high density sampling and can provide a high-resolution map of air pollution in urban areas[15,16].

In this article, biomonitoring of air pollution around Steel Group has been conducted based on the magnetic properties of evergreen tree leaves which offer a good coverage of both steel work and its ambient areas, including residential areas, recreational parks and some farmland in the western suburbs of Beijing. The aim of this work is to find out the relationship between magnetic properties and heavy metals in the studied areas, and to test the validity of the method for quantifying the environmental pollution state, and finally to provide and improve a new, fast and effective method for heavy metal pollution assessment.

1 Material and methods

1.1 Location of sampling area

Shougang Groups are located in the Shijingshan industrial area, including a series of branch steel factories, heating and power plants and other companies. The site is about 17 km west of the Tian An Men Square away and has caused serious impacts to air quality of Beijing (due to the waste discharges from all kinds of production equipments with high energy consumption, high water consumption and high discharges. The topography of Beijing area is variable. In the western and north-western parts there are dotted hills with relatively higher elevation, whereas, the city centre and eastern areas are a plain basin. The exhaust gas from steel production is further aggravated because of the topography in Beijing. Moreover, the wind direction shows an obviously seasonal variation: north and north-west winds are prevalent during the winter half year, whereas the south wind is prevalent in the summer half year. Owing to the topography and climatic condition, the pollutants derived from Shougang industrial area will be released to most parts of Haidian District and city center areas even to Chaoyang District (east of Beijing), especially when the west wind is prevalent. The studied region covers a large area limited by the Yongding River in the west and south, the west Fifth Ring in the east and west, and Badachu and Fahai Temple in the north), covering Shougang industrial area and its ambient residential areas, the recreational parks and the farmland in western suburb.

1.2 Sampling methods

Samples were taken at intervals of 1—2 km to ensure a systematic investigation integrated with a GIS-database. It was necessary to sample three different species of trees: *Sabina chinensis*, *Pinus bungeana* and *Chanaecyparis obtusa*, in order to ensure wide and homogeneous sampling coverage within the studied area. These evergreen trees were selected because of the long- term accumulation of heavy metal in leaves during the whole year. To minimize weather effects on accumulation and abrasion, the leaves were taken in clear days (April in 2004) and at least 2 weeks after rainfall. To further avoid climatic effects and to increase sample efficiency, two sampling teams operating by cars made it possible to take all the samples within two days. At each location a composite sample was collected to reduce the local effects of leaf canopy structure and resulting bias due to exposure direction. Composite samples contain leaves from different directions around the same tree and only the less than one-year old tree leaves or newest twig grown on the branch were collected. Each sample was taken from the outer canopy at a convenient sampling height of 1.5 m above the ground to minimize pollutants coming from the ground. In addition, to avoid inter-pollution during sampling, new one-off gloves were used for each sampling procedure. Samples were immediately put into pocket-sized sealable plastic bags and allowing drying at 40℃ in the lab before measurements.

1.3 Analysis methods

All magnetic measurements were conducted on leaf material directly, except for the measurement of temperature-dependent susceptibility, where the dusts dropped from leaves after drying at 40℃ were used. Mass magnetic susceptibility (χ) was measured using a KLY-3S kappabridge. Laboratory-induced anhysteretic remanent magnetization (ARM) was measured using a 2G-719 ARM alternating magnetometer with imparted 100mT peak alternating fields (AF) and a 50 μT direct current (DC) bias field parallel to the AF. IRM was generated by MMPM9 pulse magnetometer. IRM acquired in a field of 1.5 T is regarded as saturation IRM (SIRM). S ratio is defined as the ratio of IRM at a backfield of 0.3T versus SIRM. All magnetic measurements of ARM and IRM were carried out on a 2G-755 R SQUID magnetometer. Temperature dependent susceptibilities were measured with a KLY-3S Kappabridge with an attached CS-3 high-temperature furnace in argon atmosphere, through temperature cycles from room temperature to 700℃ and back to room temperature (the interval of temperature reading 2℃, heating rate: 8—10℃/min). For low-temperature dependent susceptibilities, the samples were cooled down to −196℃ by liquid nitrogen, and temperature cycles from −196℃ to room temperature were recorded. All magnetic measurements were conducted in the paleomagnetism lab of the University of Tübingen in Germany.

For elemental analysis: unwashed leaf samples were dried at 40℃ and dissolved using $HClO_4 + HNO_3 + HCl$. Total concentrations of Fe, Pb, Cr, V and Zn were determined by inductively coupled plasma-mass spectrometry (ICP-AES). Accuracy is within 5% for all elements. Elemental analyses were conducted at Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences.

2 Results and analysis

2.1 Temperature-dependent susceptibility for representative samples

Temperature-dependent magnetic properties can be used to identify the type of magnetic minerals based on their Curie-point[17,18]. High-temperature susceptibility analyses were conducted on samples 303 and 314 (collected from the residential area and the recreational park) and samples 315, 482, 468 and 484 (collected from the Shougang industrial area, and the last two taken from an iron foundry). As shown in Figure 1, temperature-dependent susceptibility of sample 303 slowly increased between 0—400℃ and slightly decreased between 400—540℃, then dropped abruptly at about 540℃, and finally decreased to the baseline at around 580℃, indicating that magnetite is main magnetic carrier. Its cooling cycle is almost reversible. Temperature-dependent susceptibilities of sample 314 rapidly decreased between 100—200℃ during heating, revealing significant paramagnetic contribution[19]. It then gradually decreased above 200℃, and abruptly dropped at about 550℃, and reached the baseline at around 580℃, again clearly indicating the presence of magnetite[20]. During the cooling cycle, the susceptibility dramatically increased at about 580℃, obviously much higher than that in heating cycles, showing that new magnetite with high susceptibility was formed during the cooling cycle. During heating, the susceptibilities of all other samples (315, 482, 468, and 484) dramatically decreased at about 580℃, indicating the Curie point of magnetite. In the cooling cycle, like for sample 314, susceptibilities rapidly increased at about 580℃, much higher than those during the heating cycles.

Figure 2 shows low-temperature- dependent susceptibilities of six representative samples. The Verwey transition at about −150℃ clearly demonstrates the existence of magnetite in all samples[21], supporting the same conclusion as by high-temperature dependent susceptibility cycles in Figure 1.

2.2 ARM acquisition and its AF demagnetization curves for representative samples

The crossover point of ARM acquisition and its AF de-

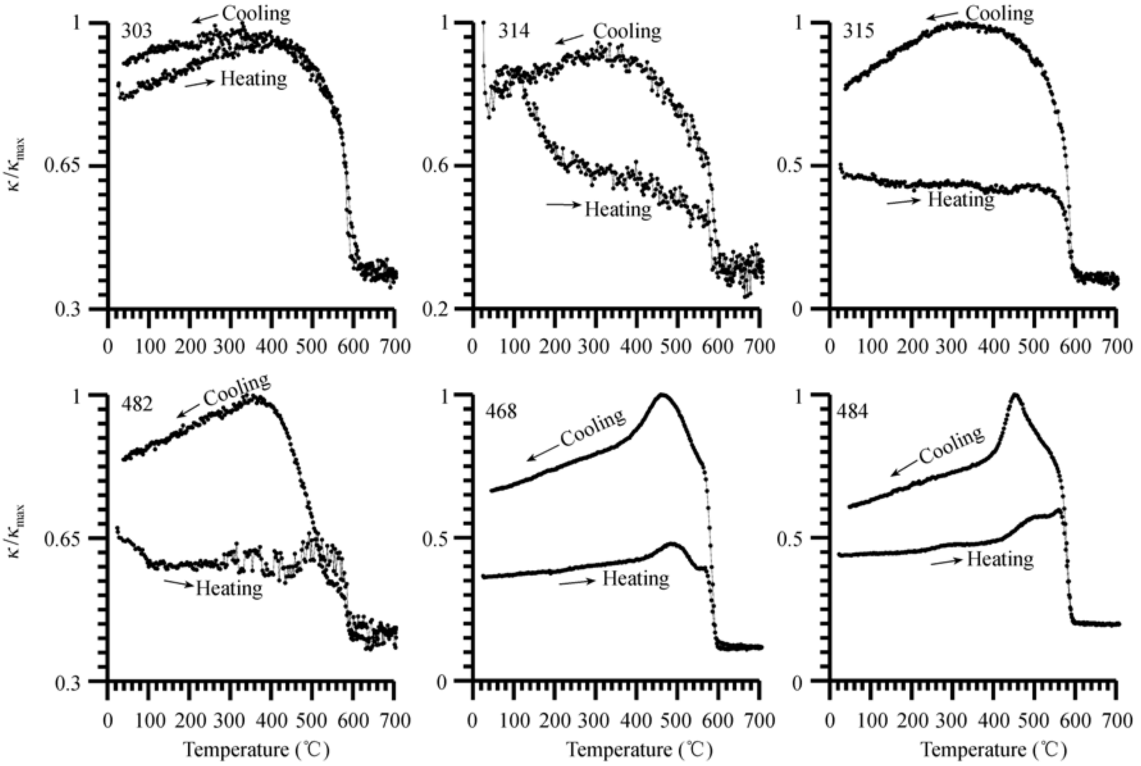

Figure 1 High-temperature-dependence of the low-field magnetic susceptibility of representative samples.

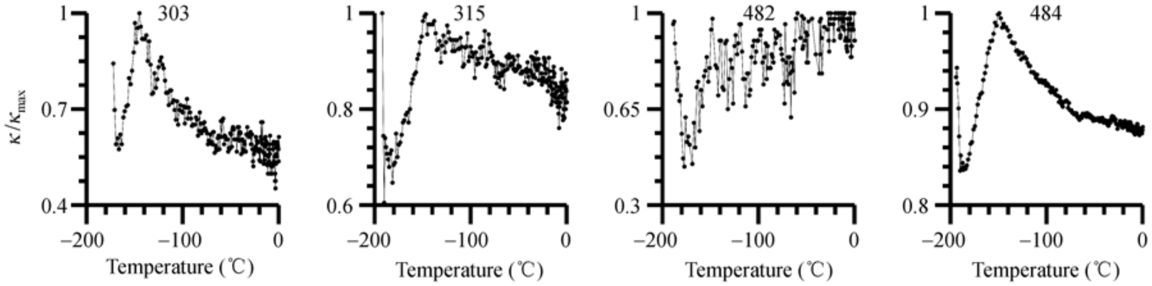

Figure 2 Low-temperature-dependence of the low-field magnetic susceptibility of representative samples.

magnetization curves can indicate the coercive force of magnetic minerals[22]. As shown in Figure 3, the cross-over points of ARM acquisition and its demagnetization curves for six representative leaf samples range among 25—30 mT, suggesting that low coercive force magnetite is the major carrier within the samples.

Figure 4 shows a significant correlation between low frequency $\chi_{\rm lf}$ and SIRM (R = 0.96), which demonstrates a predominant contribution of ferrimagnetic minerals rather than from paramagnetic, or superparamagnetic minerals. Such a linear relationship between χ and SIRM also reveals that the changes of magnetization mainly reflect changes of concentration rather than grain sizes of magnetic particles.

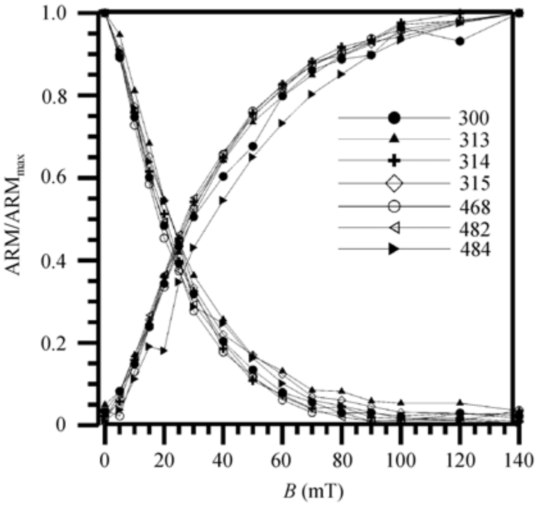

Figure 3 ARM acquisition and its back-field demagnetization curves.

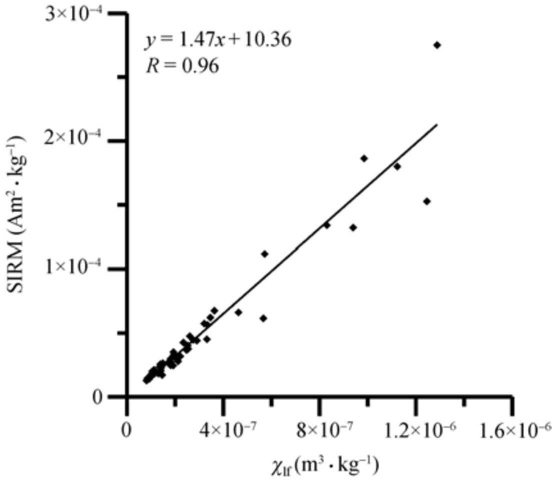

Figure 4 Linear regression analysis between susceptibility (χ_{lf}) and saturation isothermal remanent magnetization (SIRM).

2.3 Distribution of magnetic parameters for leaf samples in Shougang industrial area

Table 1 gives the minimum, maximum, mean value, and standard deviation of magnetic parameters such as χ, ARM, SIRM, S ratio, ARM/χ, ARM/SIRM and SIRM/χ for 55 leave samples. Although direct comparison of the biomagnetic background for the 3 different tree species has not been conducted, the average susceptibility of the 35 leaf samples from all 3 different tree species collected from the agricultural region in the eastern suburb of Beijing (between County Tong and Town Yanjiao, where it is relatively less or not polluted) is 11.3×10^{-8} m^3 kg^{-1} (minimum value and maximum value: 5.1×10^{-8} m^3 kg^{-1} and 17.6×10^{-8} m^3 kg^{-1} respectively, standard deviation: 3.4×10^{-8} m^3 kg^{-1}), i.e., in the same range as the susceptibility of local fluvio-lacustrine sediments. Hence, it is obvious that such a low magnetic background of leaves has no (or little) effect on the heavy metal study in the Shougang industrial area. In the Shougang industrial area, the magnetic properties of leaves are dominated by magnetic particles mixed with other heavy metals released by industry. Meanwhile, other similar studies also revealed that the biomagnetic background is less important. Hanesch et al.[8] studied two different tree species in one same street, and found that the difference between the two species is not larger than the difference between different samples taken from one tree or even one branch of a tree (but, the relative differences between samples taken from one tree can be up to 10%). Gautam et al.[9] also neglected the difference among the tree species when they studied the traffic-related heavy metal pollution in Kathmandu city using the magnetic properties of dust loaded leaves. χ and SIRM can be used for generally estimating the relative contribution from ferrimagnetic minerals, which is dependent on both the type of ferrimagnetic minerals and the grain-size of the magnetic particles[17,18]. Figure 5(a) displays a contour plot of susceptibility for leaves in Shougang industrial area. Relatively higher susceptibility values appear in a rather long and narrow area around Shougang industrial area. Within Figure 5(a), sample 208 was taken in an iron foundry; sample 216 from the third steel making plant; sample 193 from east entrance of Shougang Groups; sample 195 from a truck company of Shougang Groups; and sample 235 from waste coal ash dumps. The highest susceptibility value (128.79×10^{-8} m^3 kg^{-1}) is observed in the iron foundry. Relatively lower susceptibility values (around 8－15×10^{-8} m^3 kg^{-1}) are found in ambient areas of Shougang industrial area, including area 1$^{\#}$ (including Fahai Temple, Beijing University of Technology, and the Park Badachu), area 2$^{\#}$ (residential area and green parks located in prevailing wind direction of industrial area), and area 3$^{\#}$ (less polluted area situated in the western suburb), where the lowest susceptibility value, (8.1×10^{-8} m^3 kg^{-1}), is observed. Such relatively lower susceptibility is in the same order as the average susceptibility of 35 leaf samples collected from the eastern suburb as mentioned above. Thus, this value can be considered as the natural magnetic background of the tree leaves in this area. Figure 5(c) shows the contour plot of SIRM for leaves in Shougang industrial area. Its spatial distribution pattern is similar to that of χ (Figure 5(a)). Meanwhile, there is a strong correlation between SIRM and χ (Figure 4),

Table 1 Statistics of magnetic parameters (n = 55)

	χ (10^{-8} m^3 kg^{-1})	SIRM (10^{-6} Am^2 kg^{-1})	ARM (10^{-6} Am^2 kg^{-1})	S ratio	SIRM/χ (KA/m)	ARM/χ (10^2A/m)	ARM/SIRM
Minimum value	8.10	1272.36	17.10	0.88	10.86	1.12	0.007
Maximum value	128.79	27510.82	244.57	0.98	21.36	2.69	0.015
Mean value	30.25	4887.91	54.91	0.92	16.07	2.01	0.013
Standard deviation	29.93	45.81	45.81	0.01	2.09	0.33	0.001

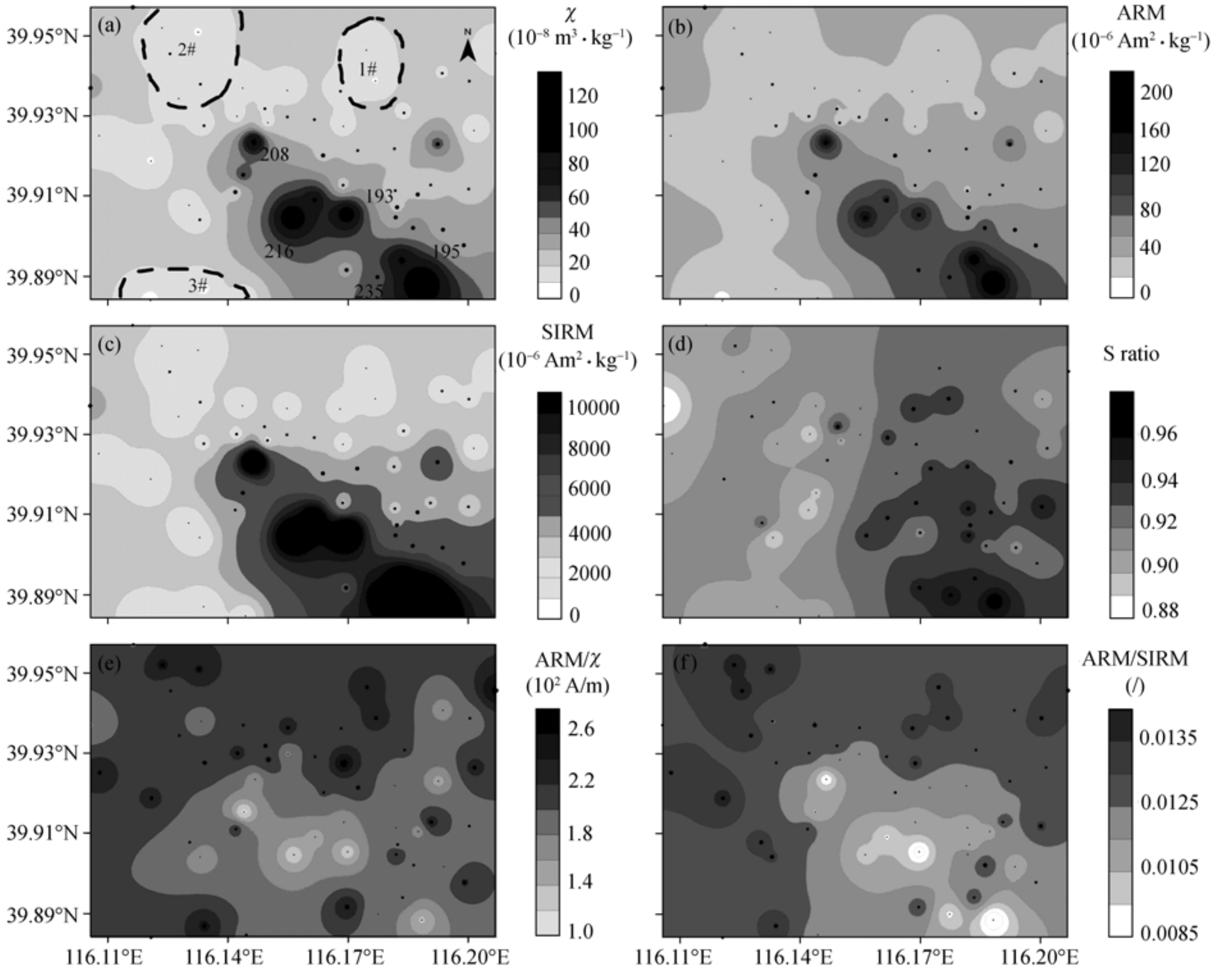

Figure 5 Contour maps of magnetic parameters (the areas defined by dashed lines are #1, #2 and #3 areas mentioned in the text; the closed circles are sampling sites).

which further confirms that ferrimagnetic minerals are the predominant magnetic carrier in the samples[23,24]. The leaf itself is diamagnetic and weakly magnetic in less industrialized areas, which might lead to a relative high measurement error. However, the isothermal remanent magnetization (IRM) is acquired under artificial fields applied in lab. Thus, it might intensify anthropogenic pollution signals, and yield better results in comparison with low susceptibility. In the studied area, SIRM and χ have the same spatial distribution patterns with an excellent correlation between them ($R = 0.96$). The two parameters can, therefore, be assumed as representative of the amount of ferrimagnetic particles. Furthermore, in this study, the susceptibility for leaves is normalized by its mass. We suppose that the susceptibility of dust accumulated on a leaf per volume can represent that of the whole leaf and there is a good liner relationship between its susceptibility per volume and per mass. As shown in Figure 5, the spatial distribution of susceptibility looks reasonable. Hence, the above-mentioned hypothesis is tenable. Of course, the best way should be only to collect all dust accumulated on leaf rather than a leaf itself. But it is very difficult to do so in practice, especially when studying a large area with a high resolution sampling procedure. Until now, measurements were conducted only on whole-leaf sample rather than the dust dropped from the leaf reported in many other studies too[7−14].

The ARM is dependent on both type of magnetic minerals and their grainsizes, and is most sensitive to the presence of single domain (SD) magnetic particles[25]. In this study, the spatial distribution pattern of ARM is similar to χ (Figure 5(b)), which may testify that ARM is controlled mainly by concentration of ferrimagnetic minerals rather than by their grainsizes[10].

The S ratio indicates the relative contribution of ferrimagnetic and antiferrimagnetic minerals[25]. As shown in Table 1, the S ratio values ranging from 0.88 to 0.98, with a mean value of 0.92, indicates the predominance of ferrimagnetic components[26,27]. Higher S values are found in Shougang industrial area and its eastern parts (Figure 5(d)), interpreted as higher concentration of ferrimagnetic minerals. Besides, it is worth to point out that the average value of SIRM/χ is 16.07 kA/m, close to those reported by Moreno et al.[12] and Shu et al.[28]. Such a value is normally related to multi-domain (MD) magnetite contained within industrial fly ash very common. The corresponding average values of SIRM/χ are 14 kA/m[12] and 12－16 kA/m[28], while the artificial magnetic fields applied to acquire SIRM were 0.9 T and 1 T respectively.

The ARM/χ ratio depends on the composition and the grainsize of the magnetic particles. When the magnetic mineralogy is homogeneous, ARM/χ and ARM/SIRM ratio indicates the variation of the grainsize of the magnetic minerals. In general, both lower ARM/χ and ARM/SIRM indicate coarse grains of magnetite, whilst higher ratios indicate fine grains, especially SD grains[24,29]. As shown in Figure 5e and f, in the vicinity of heavily polluted Shougang industrial area, both lower ARM/χ and ARM/SIRM hint towards predominant coarse magnetic particles, while in its ambient areas, both higher ARM/χ and ARM/SIRM indicate fine ones.

Summarizing, magnetic concentration is relatively higher, and ferrimagnetic grains are coarser in and nearby pollution sources (Shougang industrial area); while concentration is lower and grains are finer at far distance from the pollution source. Therefore, for the pollutants the transportation mode results in higher concentration of magnetic particles with coarser grainsize in heavily polluted areas, but decreasing in concentration and increasing in grainsize as the pollutants transport over longer distance.

2.4 Heavy metal contents of leaf samples

As shown in Table 2, there is a big difference between the minimum and the maximum value of the tested elements. The maximum value is as around three times as the minimum. The minimum value is very close to the average value of 18 leaf samples collected from the agricultural region in the eastern suburb (as mentioned above between Tong County and Yanjiao Town). The average content of Fe, Pb, Cr, V and Zn are 732.92, 4.52, 1.45, 1.27 and 21.09 mg/kg respectively in the eastern suburb. The minimum value of heavy metal contents can be considered as the background in the studied area. Hence, the big difference between the minimum and the maximum value of the elements in leaves may reflect anthropogenic inputs. Shougang industrial area is a very complex pollution source, with coking, power generating, sintering, iron making and steel making plants where coking plants and power plants are the major sources releasing magnetic minerals during dry distillation and combustion of coals. Some results[30,31] showed that the average content of Pb in the coal in China is about 19.96 mg/kg. Pb contained in the coal and petroleum will convert to low fusing point chloride during the burning process, and is then released into the atmosphere. Some authors found that the toxic element V originates from fossil fuel combustion and exhibits a gradually increasing trend around the industrial areas[32,33]. Furthermore, Lindstrom[34] also observed that the Cr content was obviously higher than that around smelt and metal processing plants, and was enriched remarkably in moss nearby. Pb and Zn can be directly released into the atmosphere through vehicle’s transportation of raw material and products in/around Shougang industrial area[35]. The above-mentioned reasons can explain why big differences between the elements exist.

Table 2 Statistics of heavy metal contents (n = 24)

(mg/kg)	Fe	Pb	Cr	V	Zn
Minimum value	631.11	4.39	1.26	1.01	19.97
Maximum value	2253.91	11.56	4.26	3.37	45.96
Mean value	1113.47	7.30	2.00	1.63	28.00
Standard deviation	448.0	2.03	0.74	0.54	6.66

3 Discussions

In order to judge how close the variables (magnetic parameters and heavy metals) are related to each other, a tree diagram (Figure 6) is constructed (variables are standardized, then processed with SPSS software). The abscissa represents the interval between the variables within the figure; the shorter the distance the higher the correlation. As shown in Figure 6, the average distance between elements (Fe, Pb, Cr, V and Zn) and magnetic concentration parameters (χ, ARM and SIRM) is smaller than 5, which suggests that there is a strong correlation between them, also confirmed by the correlation coefficients in Table 2. All the correlation coefficients be-

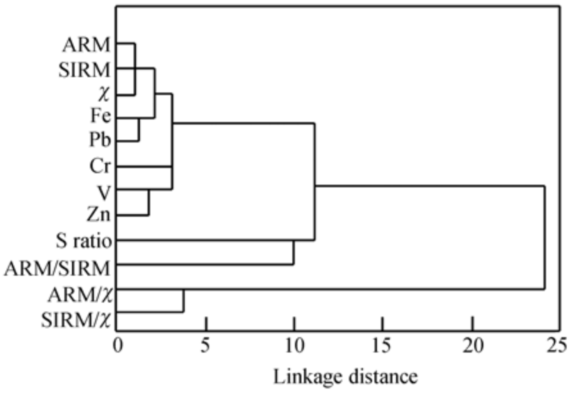

Figure 6 Tree diagram derived from cluster analysis of magnetic parameters and heavy metals.

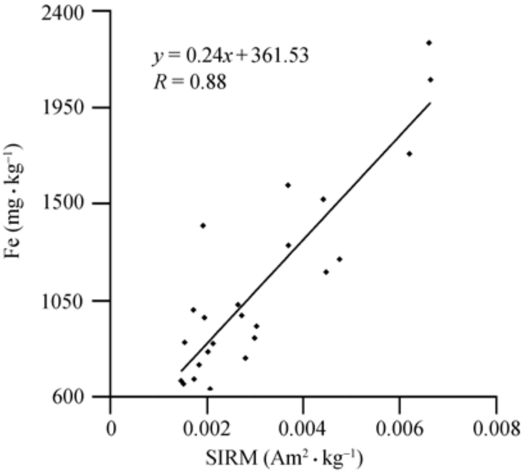

Figure 7 Linear regression analysis between SIRM and total iron content.

tween magnetic parameters (χ, ARM and SIRM) and elements (Fe, Pb, Cr, V and Zn) are greater than 0.73, reflecting that the magnetic mineral and elements originate from the same pollution source. However, the above-mentioned elements are relatively less correlated with magnetic parameters indicating relative mineral composition ratios (S ratio, ARM/SIRM, ARM/χ and SIRM/χ).

Many authors have emphasized the correlation between the magnetic minerals and heavy metals on dust in suspension. Hansen et al.[36] observed that Fe, Pb, V, Cr, Zn and Ni contained in fly ash from coal combustion in industrial production are mostly related to with magnetic minerals, and found that Fe, O, Si and Zn are strongly correlated with magnetic spheres derived from steel work. Lauf et al.[37] observed there existed a correlation between the magnetic spheres and heavy metals in dust derived from coal combustion and mentioned that magnetic spheres were converted from pyrite during coal combustion. In Shougang industrial area, being a very complex pollution sources, the magnetic particles, derived mostly from combustion and smelting procedures, may remain in air for some time, but most of them finally deposit on the leaves around the pollution sources. Both magnetic minerals and heavy metals deriving from the same source is the main reason for the significant correlation between them. An excellent linear correlation (R = 0.88) between the SIRM and the total iron content can be found in Figure 7. For zero magnetization the calculated regression line intercepts the y-axis at an iron content of 361.53 mg/kg, which is ascribed to biogenic iron[7]. It is suggested that biogenic iron is diamagnetic. A close correlation of SIRM and Fe content shows that non-destructive, time-efficient environmental magnetism of leaf can perfectly preserve the magnetic properties for a long time. Furthermore, there is a strong linear correlation ($0.73 \leqslant R \leqslant 0.88$) between magnetic concentration parameters (χ, ARM and SIRM) and heavy metals (Fe, Pb, V, Cr and Zn) in Table 3. Despite the dependence of magnetic parameters and heavy metal contents on a variety of spatial and temporal factors, the excellent linear correlation between them suggests the former can serve as an effective proxy for heavy metal pollution. Hence, a susceptibility-based biomonitoring technique is recommended as an economic and fast tool for assessment of environment pollution in urban areas like Beijing. The regression equations between low frequency susceptibility ($\chi_{\rm lf}$) and heavy metal content are established in Figure 8. Hence, we can roughly estimate the selected heavy metal content by rapid, sensitive magnetic mapping on tree leaves in industrial area by the help of integrated data processing in lab.

Table 3 Correlation matrix (R) for magnetic parameters and heavy metal contents (n = 24)

	Fe	Pb	Cr	V	Zn
χ	0.88	0.84	0.82	0.79	0.78
SIRM	0.88	0.82	0.75	0.73	0.80
ARM	0.87	0.85	0.77	0.74	0.78
S ratio	0.34	0.35	0.33	0.15	0.38
ARM/χ	0.49	0.48	0.50	0.43	0.32
ARM/SIRM	0.48	0.56	0.39	0.36	0.27
SIRM/χ	0.25	0.18	0.18	0.32	0.19

It is worth to be pointed out that a variety of spatial and temporal factors will affect the dust disposition and the amount of accumulation on leaves, such as human

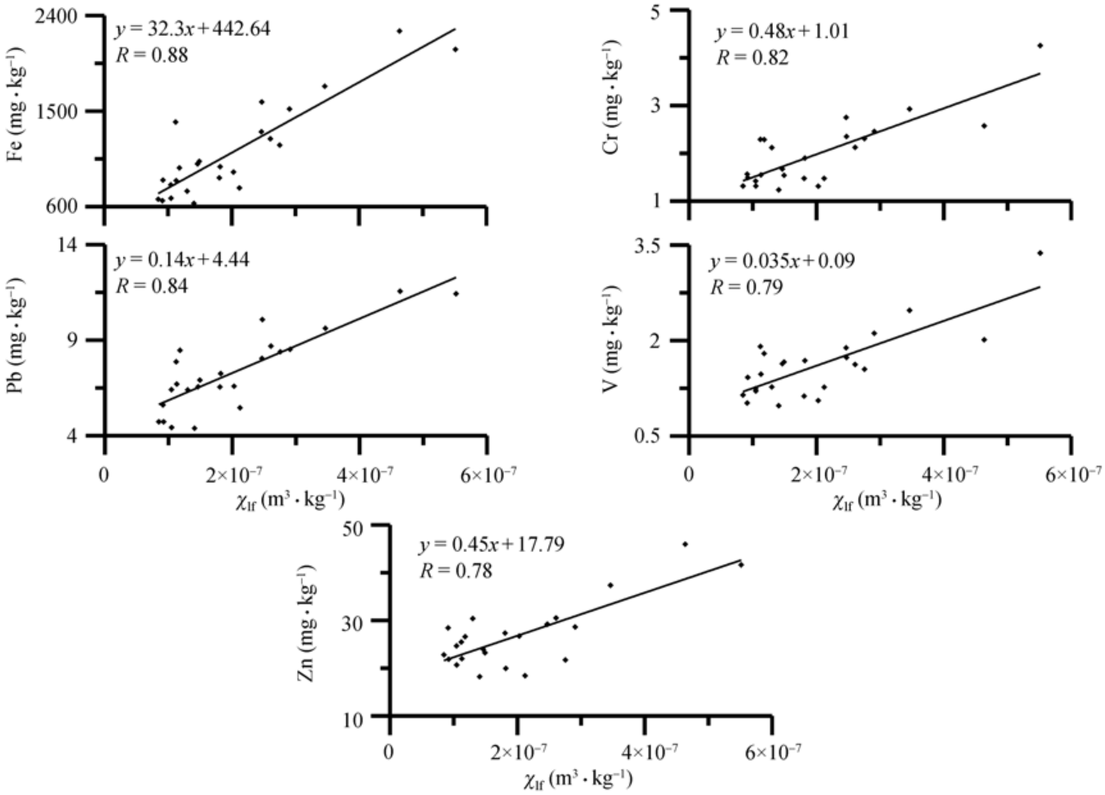

Figure 8 Linear regression analysis between susceptibility (χ_{lf}) and element contents (Fe, Pb, V, Cr and Zn) (n = 24).

activities, efficiency of disposition, leaf canopy structure, exposure direction, precipitation, wind direction, wind speed etc. Hence, magnetic measurement in terms of anthropogenic and lithogenic origin identified by a regional experimental model of the relationship between magnetic properties and heavy metals will help to outline the spatial and temporal extent of atmospheric pollution in industrial areas. Besides monitoring, we see an urgent need for characterization and quantification of the particles in different environmental systems (atmosphere, soil, vegetation, water, etc.) using rapid and cost-effective techniques, such as combined environmental, magnetic and analytical chemical methods.

4 Conclusions

(1) The main magnetic mineral carried by the dust-loaded leaf sample is low-coercivity magnetite. Its concentration and grainsize are higher in a relative long and narrow area centering in the Shougang Groups, and gradually decrease as distance from the pollution source increases;

(2) There is an evident correlation ($0.73 \leqslant R \leqslant 0.88$) between the magnetic parameters (χ, ARM and SIRM) and elements (Fe, Pb, Cr, V and Zn), demonstrating that magnetism can serve as a good proxy for heavy metal pollution. Rapid, sensitive magnetic mapping of tree leaves integrated with data processing can help to build a regional experimental model of the relationship between magnetic properties and heavy metals for assessment of atmospheric pollution in urban areas like Beijing;

(3) For monitoring heavy metal pollution, leaf has many advantages, such as widely spread, easily available and the low background. It is convenient to provide a high density of sampling points and building high-resolution maps of air pollution. Hence, susceptibility-based bio-monitoring technique is recommended as an economic and rapid tool for assessment of environment pollution in urban areas like Beijing.

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