Journal of Applied Geophysics 74 (2011) 1–7

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Relationships between magnetic susceptibility and heavy metals in urban topsoils in the arid region of Isfahan, central Iran

Rezvan Karimi, Shamsollah Ayoubi *, Ahmad Jalalian, Ahmad Reza Sheikh-Hosseini, Majid Afyuni

Department of Soil Science, College of Agriculture, Isfahan University of Technology, Isfahan, 84156–83111, Iran

ARTICLE INFO

Article history:
Received 4 September 2010
Accepted 15 February 2011
Available online 23 February 2011

Keywords:
Heavy metals pollution
Isfahan
Magnetic susceptibility
Urban soils

ABSTRACT

Recently methods dealing with magnetometry have been proposed as a proper proxy for assessing the heavy metal pollution of soils. A total of 113 topsoil samples were collected from public parks and green strips along the rim of roads with high-density traffic within the city of Isfahan, central Iran. The magnetic susceptibility (χ) of the collected soil samples was measured at both low and high frequency (χlf and χhf) using the Bartington MS2 dual frequency sensor. As, Cd, Cr, Ba, Cu, Mn, Pb, Zn, Sr and V concentrations were measured in the all collected soil samples. Significant correlations were found between Zn and Cu (0.85) and between Zn and Pb (0.84). The χfd value of urban topsoil varied from 0.45% to 7.7%. Low mean value of χfd indicated that the magnetic properties of the samples are predominately contributed by multi-domain grains, rather than by super-paramagnetic particles. Lead, Cu, Zn, and Ba showed positive significant correlations with magnetic susceptibility, but As, Sr, Cd, Mn, Cr and V, had no significant correlation with the magnetic susceptibility. There was a significant correlation between pollution load index (PLI) and χlf. PLI was computed to evaluate the soil environmental quality of selected heavy metals. Moreover, the results of multiple regression analysis between χlf and heavy metal concentrations indicated the LnPb, V and LnCu could explain approximately 54% of the total variability of χlf in the study area. These results indicate the potential of the magnetometric methods to evaluate the heavy metal pollution of soils.

1. Introduction

Dust that accumulates on soils and roadsides in the urban and industrial areas is indicator of heavy metal contamination from atmospheric deposition (Culbard et al., 1988). Method based on the Magnetometric properties of soils are increasingly applied as proxy methods for evaluating the heavy metal pollution of soils, sediments and dusts, because such methods are rapid, inexpensive and non-destructive and can be used for mapping of the contaminated soils (e.g., Wang and Qin, 2005). In addition, the interest in the use of magnetometric methods is increasing because of their rapidity as a single measurement of soil samples makes it possible to establish dense grids of sampling sites (Hanesch and Scholger, 2002).

There have been numerous studies linking the magnetic properties of soils to the urban contamination in a variety of environments. For example, Lu and Bai (2006) reported that soils near urban and industrial areas had an increased magnetic susceptibility, which they attributed to the deposition of magnetic particles such as dust from the metallurgical industry and fly ash from coal combustion. Strzyszcz and Magiera (1998) reported relatively high correlation coefficients between concentrations of Zn, Pb, and Cd in forest soils of the Upper Silesian industrial regions (Southern Poland) and magnetic susceptibility. Magnetic properties and heavy metal concentration (Cu, Cr, Pb, Ni, and Zn), which were measured on vibracore samples, were found to be potential indicators of the contamination of seabed sediments due to the shipping activities in the Hong Kong Harbor (Chan et al., 2001). The whole-core magnetic susceptibility measurements showed a higher concentration of magnetic particles in the surface layer of the sediment cores, and significant correlations were observed between the magnetic susceptibility and concentrations of Pb, Zn and Cu, as well as the Tomlinson pollution load index (PLI).

Lecoanet et al. (2003) assessed the potential of the magnetic techniques to determine the contaminating emission sources and its effects on the contamination of surface and bottom soil samples. The results showed that the contents of magnetic minerals with higher magnetic coercivity increased with depth from surface to the bottom in the soil profiles.

The scanning electron microscopy (SEM) analysis was used to study the surface soil samples collected from Xuzhou, a large industrial city in China that is a center for mining and heavy industries

---

Abbreviations: χlf, Low frequency magnetic susceptibility; χhf, High frequency magnetic susceptibility; χfd, Frequency-dependent susceptibility; As, Arsenic; Cd, Cadmium; CU, Copper; Ba, Barium; Sr, Strontium; Cr, Chromium; V, Vanadium; Mn, Manganese; Zn, Zinc; Pb, Lead; MS, Magnetic susceptibility; PLI, Pollution load index; K–S, Kolmogorov–Smirnov; Fe, Iron; EC, Electrical conductivity; pH, Soil acidity; SOM, Soil organic carbon; CCE, Calcium carbonate equivalent; CEC, Cation exchangeable capacity.

* Corresponding author. Tel.: +98 3113913470; fax: +98 3113913471.
E-mail address: ayoubi@cc.iut.ac.ir (S. Ayoubi).

0926-9851/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jappgeo.2011.02.009

(Wang and Qin, 2005). Magnetic minerals in the topsoil samples were found in the form of spherules and mainly originated from the anthropogenic inputs. In addition, the authors showed that Pb, Cu, Zn, Se, Sc, Mo, Fe, and Bi concentrations were highly correlated with the magnetic susceptibility. The concentrations of Ag, Ba, Cd, Ni, Cr, Sb, and Sn, on the other hand, had weak correlations with magnetic susceptibility. The Tomlinson pollution load index (PLI) was also significantly correlated with the magnetic susceptibility.

A further study of the urban soils in Hangzhou, eastern China revealed a positive correlation between magnetic properties and Cu, Zn, Cd and Pb concentrations (Lu and Bai 2006). Magnetic parameters χ, ARM, $\mathrm{IRM}_{20\ \mathrm{mT}}$, Hard IRM and SIRM increased in the order of industrial area > roadside > residential ≈ campus > public parks and the trend was nearly in the line with the changes in the concentrations of Pb, Cu, Zn and Cd. The source of the magnetic minerals was attributed to the industrial activity, automobile exhaust and the deposition of atmospheric particulate matter. Contrary to Cu and Cd that had low correlation with studied magnetic properties, Zn showed the highest correlation and Pb showed medium correlation with magnetic properties (Lu and Bai, 2006). The results of the study by Lu et al. (2007) for the soils in Hangzhou confirmed the results reported in the study on the significant relationship between Cr, Cu, Pb and Zn concentrations and the magnetic susceptibility and SIRM.

Comparison of the results for surface soil samples collected from urban and agricultural sites in Shanghai using magnetic techniques for monitoring soil pollution showed that compared with the background, magnetic signals of the urban topsoils greatly increased with the magnetic susceptibility, while those of the agricultural surface soil samples were only slightly increased (Hu et al., 2007). Their results suggest that coarse-grained ferromagnetic particles were deposited on the urban topsoils, therefore indicating that the extra magnetic minerals accumulated in the urban topsoils are neither inherited from soil parent materials nor from the pedogenic processes, but originate from anthropogenic activity.

The analytical results of Lu et al. (2008) are in accordance with the accumulation of heavy metals and magnetic minerals in soils along an urban–rural gradient in Hangzhou city, China and indicated that heavy metal concentrations and magnetic susceptibility (χlf) in soils decreased with distance from the urban center of Hangzhou. There were significant statistical correlations between heavy metal concentrations, χlf and distance from the urban center. The soils in the urban areas were enriched with Cd, Cu, Pb and Zn and thus provide evidence for the accumulation of heavy metals through anthropogenic activities (Lu et al., 2008).

However, no study has been reported on the monitoring of metal pollution of soils using the magnetometric methods in Iran. Therefore, the objectives of this study were to (i) to characterize the Zn, Pb, Cu, Ba, Cr, As, Mn, Cd, Sr and V concentrations in topsoils and (ii) to examine the feasibility of using the magnetic susceptibility for the heavy metal pollution assessment of urban topsoils in the arid region of Isfahan, central Iran.

2. Materials and methods

2.1. Study site and sampling

This investigation was conducted in the city of Isfahan, a city in central Iran with a population of 1.6 million inhabitants. The study area extends from 51°31′30″ E to 51°45′29″ E longitude and 32°35′ N to 32°47′47″ N latitude, encompassing an area of approximately 324 km^2 around the Zayandehroud river, which flows from west to southeast (Fig. 1). The parent rock materials are mainly recent river (?) terraces and alluvial deposits, and undifferentiated terraces all of Quaternary age. The soils of this region are Aridisols belonging to different suborders, such as Calciargids, Haplocambids, Haplogypsids and Haplosalids. The average annual rainfall and temperature of the region are 140 mm and 14.5 °C, respectively.

A total of 113 soil samples (0–10 cm depth) were collected from the study area (Fig. 1). Sampling sites were selected from the green vegetated space of roadsides and public parks. Roadside soil samples were collected from the locations along the rim of road, including highways and high-density traffic streets. At each sampling point, three sub-samples were taken over a 5 × 5 m surface, and then mixed to obtain a bulk sample. Such a sampling strategy was adopted to reduce the possibility of random influence of urban waste not clearly visible. All the samples were collected using a stainless steel spatula and were stored in PVC sample bags. Before analyses, the soil samples were air-dried and sieved through a 2-mm sieve.

2.2. Magnetic susceptibility measurement and laboratory analyses

Magnetic susceptibility (χ) was measured at low (0.47 kHz; χlf) and high frequencies (4.7 kHz; χhf), respectively using a Bartington MS2 dual frequency sensor. The χ value is dependent on the concentration of ferrimagnetic minerals within a sample, although it is also sensitive to magnetic grain size (Lu and Bai, 2006). Frequency-dependent susceptibility (χfd), which indicates the presence of superparamagnetic (SP) grain sizes, was calculated using Eq. (1):

$$\chi\mathrm{fd}(\%) = [(\chi\mathrm{lf} - \chi\mathrm{hf}) / \chi\mathrm{lf}] \times 100 \qquad (1)$$

Soil samples (0.2 g) were dissolved in a hot HF-HNO3-HCl acid mixture (15 ml), and refluxed with the acid mixture if the sample was only partly dissolved. Arsenic, Cd, Cr, Ba, Cu, Mn, Pb, Zn, Sr, and V concentrations were measured by inductively coupled plasma mass spectrometry (ICP-MS). Soil pH was measured in saturated soil using a glass electrode (McLean, 1982) and electrical conductivity (EC) of the saturated extract was determined using a conductivity meter (Sarkar and Haldar, 2005). Calcium carbonate equivalent (CCE) was measured by Bernard's calcimetric method (USDA, 1996). Soil organic matter (SOM) was determined using the wet combustion method (Nelson and Sommers, 1982) and cation exchange capacity (CEC) by extraction with sodium acetate (Rhoades, 1982). Percentages of clay, sand and silt were measured using the Hydrometer method (Gee and Bauder, 1986).

2.3. Statistical analysis and pollution index calculation

Descriptive statistics including the mean, standard deviation, minimum, maximum, median, range, kurtosis and skewness were determined. Pearson linear correlations among various parameters were calculated using SPSS software (Swan and Sandilands, 1995) and used to interpret the relationships between heavy metals and soil properties.

A stepwise regression procedure was used to regress magnetic susceptibility on the heavy metal concentration. Selection of factors for inclusion in the model was based on probability ≤0.05 (Freund and Littell, 2000). Magnetic susceptibility was the dependent variable and the heavy metal concentrations were the independent variables. The models were of the following form:

$$Y = b_o + b_1F_1 + b_2F_2 + \ldots + b_nF_n + \varepsilon \qquad (2)$$

Where Y represents estimated magnetic susceptibility, $\mathrm{b_o}$ to $\mathrm{b_n}$ are coefficients, $\mathrm{F_1}$ to Fn are the metal concentrations and ε represents residual error. The selection of the best predictive model was performed based on determination coefficient (R^2).

The integrated pollution index for the ten metals was used to assess the soil environmental quality (Tomlinson pollution load index,

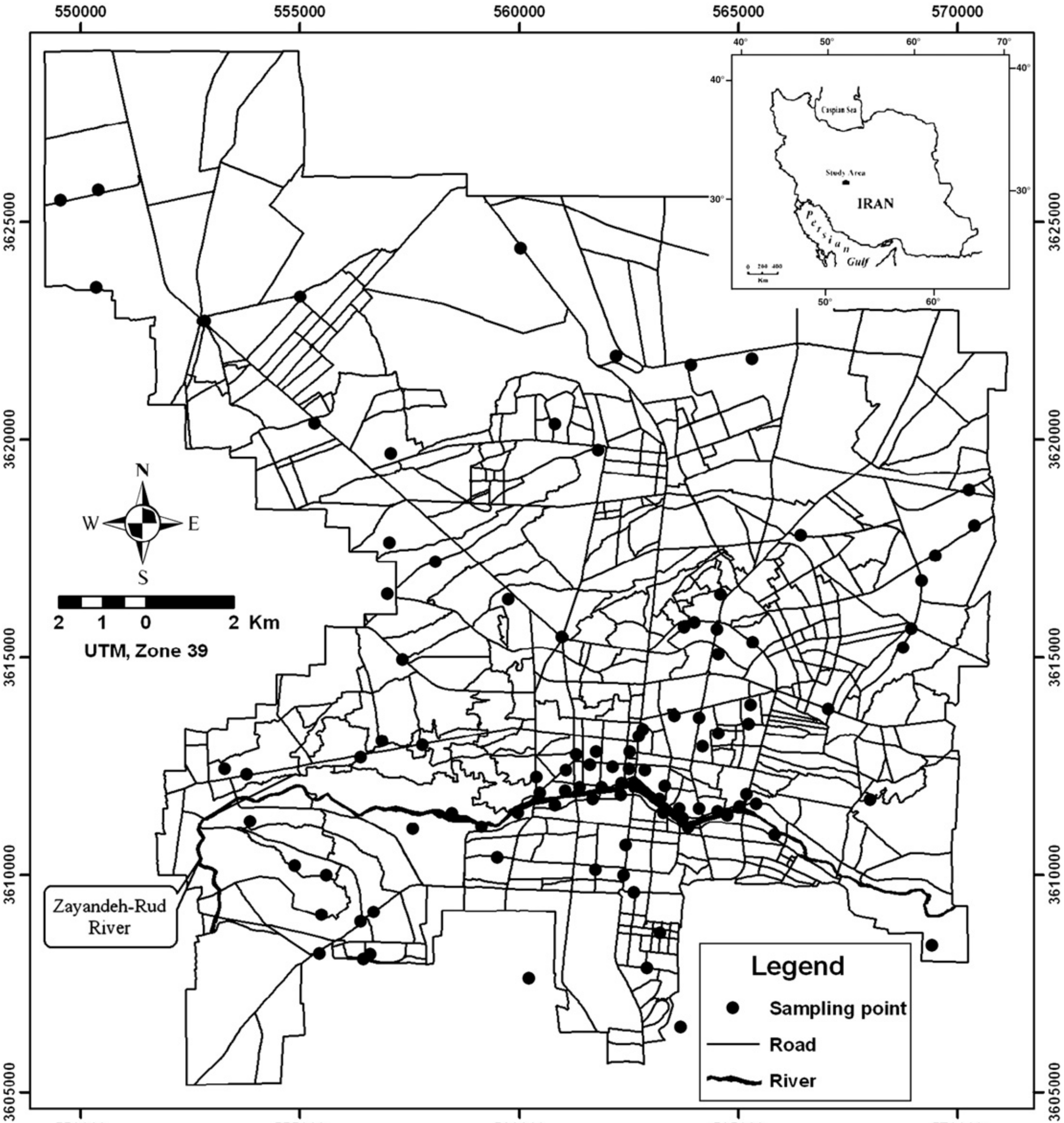

Fig. 1. Sketch map of the Isfahan city with the location of sampling sites, located at central Iran.

PLI). According to Angulo (1996) PLI is the nth root of the product of the different metal concentrations (CF_{metal}):

$$PLI = \sqrt[n]{\prod_{k=1} CF_{metal}} \tag{3}$$

where CF_{metal} is the ratio between the concentrations of each heavy metal to the background values, i.e. $CF_{metal} = CH_{metal}/CH_{background}$. The PLI gives an assessment of the overall toxicity status for a sample, which is a result of the contribution of ten heavy metals. In this study, the lowest concentration of each type of heavy metal detected in the samples was used as the background for that type of heavy metal.

3. Results and discussion

3.1. Descriptive statistics

The descriptive statistics of heavy metal concentrations and soil properties are presented in Table 1. All the soil properties were normally distributed according to Kolmogorov–Smirnov (K–S) test except for the EC and CEC. Skewness values (Table 1) also confirmed the results as they that showed low deviation from normality, except for the EC and CEC. Among selected heavy metal concentrations, the application of K–S test indicates that except for Cd, Mn V, and Cr, other heavy metals were not normally distributed. This obviously indicates a deviation of the contents of these metals from the natural background concentration. In order to have correlation and multiple regression analyses it is necessary to apply the normal data, so the abnormal data were transferred to achieve normality using natural logarithm transformation. For example the distribution data of Sr concentration in the study area before and after normalization are presented in Fig. 2.

The soils are neutral to slightly alkaline. Soil EC varies from 0.5 to 14.5 $dS\,m^{-1}$. The soils are mostly loam with an average of clay content of 37 $g\,kg^{-1}$. The average SOM content in the region is low (1.5%) but variable. The variability of SOM is mainly due to the anthropogenic activity, such as the use of manure, sludge and compost as soil amendments. CEC has a mean value of 25.21 Cmol $(+)\,kg^{-1}$ in the soils studied, ranging from 4.5 to 73 Cmol $(+)\,kg^{-1}$.

3.2. Relationships between soil parameters and trace elements

The correlation coefficients between the heavy metals and various soil properties are shown in Table 2. The correlation of clay content

Table 1
Descriptive statistics of soil properties and heavy metal contents in urban soils of Isfahan city, central Iran (N = 113).

Variable	Unit	Minimum	Maximum	Mean	S.D	Skewness	Kurtosis	Range
χlf	10^{-8} m^3 kg–^{1}	26.50	123.18	74.34	19.39	1.17	1.59	96.68
χfd	(%)	0.45	7.70	3.96	1.59	0.22	−.045	7.25
Mn	mg kg–^{1}	378	735.00	556.87	58.31	0.00	1.60	357.00
Sr	mg kg–^{1}	227	987.00	454.52	142.62	1.65	3.55	760.00
Ba	mg kg–^{1}	6	201.00	106.85	22.45	1.30	2.89	139.00
Cd	mg kg–^{1}	0.50	1.10	0.64	0.14	0.74	−0.25	0.60
Pb	mg kg–^{1}	15.00	198.00	44.25	35.50	2.78	8.66	183.00
Zn	mg kg–^{1}	47.00	306.00	102.04	43.18	2.21	6.47	259.00
Cu	mg kg–^{1}	12.00	94.00	38.50	15.07	1.06	1.78	82.00
As	mg kg–^{1}	4.00	15.00	7.06	1.52	1.30	6.32	11.00
V	mg kg–^{1}	21.00	48.00	38.63	4.63	−0.97	2.31	27.00
Cr	mg kg–^{1}	21	55.00	43.38	6.25	−0.94	2.13	35.00
Sand	%	0.96	79.00	27.11	16.35	0.98	0.72	79.00
Silt	%	11.00	70.00	35.87	10.81	0.30	0.47	59.00
Clay	%	2.50	60.00	36.97	11.24	−0.357	0.49	57.00
EC	dS m–^{1}	0.70	14.5	3.62	5.23	4.07	23.22	10.80
pH		7.20	8.30	7.72	0.26	0.23	−0.69	1.10
SOM	%	0.06	4.21	1.50	0.96	0.55	−0.06	4.15
CCE	%	9.80	59.00	31.14	10.08	−0.16	−0.87	49.2
CEC	Cmol(+) kg–^{1}	4.5	73.00	25.21	16.15	1.31	0.63	68.50

S.D: standard deviation; χlf: low frequency magnetic susceptibility; χfd: frequency-dependent susceptibility; Mn: manganese; Sr: strontium; Ba: barium; Cd: cadmium; Pb: lead; Zn: zinc; Cu: copper; As: arsenic; V: vanadium; Cr: chromium; EC: electrical conductivity; pH: soil acidity; SOM: soil organic carbon; CCE: calcium carbonate equivalent; and CEC: cation exchangeable capacity.

with Zn, Cu, Sr and Cr was significant (Table 2). Chen et al. (1999) reported that concentrations of Cr, Pb, Zn and Cu amongst others were correlated with clay in the surface soils of Florida and suggested that clay is the main soil component related with the heavy metals accumulation in topsoils.

Soil organic matter content showed positive significant correlations with Pb, Zn, Cu, Sr, Cr, and Mn (Table 2). These results indicate the affinity of the heavy metals to form organic complexes (J. Rustullet, 1996). Mico et al. (2006) and Rodríguez Martín et al. (2006) reported a positive correlation between heavy metal concentrations and organic matter content and pointed out that soil organic matter is an important sink for the heavy metals.

Soil pH and EC did not significantly correlate with the heavy metal concentration in the study area. Soil pH is restricted to a narrow range of 7.2 to 8.3. The neutral-subalkaline condition restricts the mobility of all heavy metals, so that it had a limited importance to heavy metal distribution. These results are consistent with the findings of Manta et al. (2002) in Palermo, Italy. Cation exchange capacity showed positive correlations with Cu and Cr concentrations. The concentration of these elements was also significantly correlated with clay content and SOM.

3.3. Correlation among elements

The correlation coefficients among the selected heavy metals are presented in Table 3. Lead correlated positively with Zn, Cu, Cd and Cr. Chromium exhibited a wide association with Zn, Cu, Mn and V. The highest correlation coefficients were found between Pb and Zn, Zn and Cu and Cr and V. These results agree with those reported by Rodríguez Martín et al. (2006), who demonstrated significant correlations between Zn and Pb (r = 0.68) and between Cu and Zn (r = 0.66). Nan et al. (2002) studied soils under wheat cultivation in China and reported highly significant correlations between Zn and Cu (r = 0.88) and between Zn and Pb (r = 0.80), which agree with results obtained in the present study.

3.4. Distribution of magnetic susceptibility

Summary statistics for the specific susceptibility for all the studied soil samples are presented in Table 1. The mean value of specific susceptibility is 74.34×10^{-8} kg. For comparison, the mean values of χlf in the urbanized soil of the Isfahan is higher than the values measured by Ayoubi et al. (2002) in natural topsoils east of Isfahan

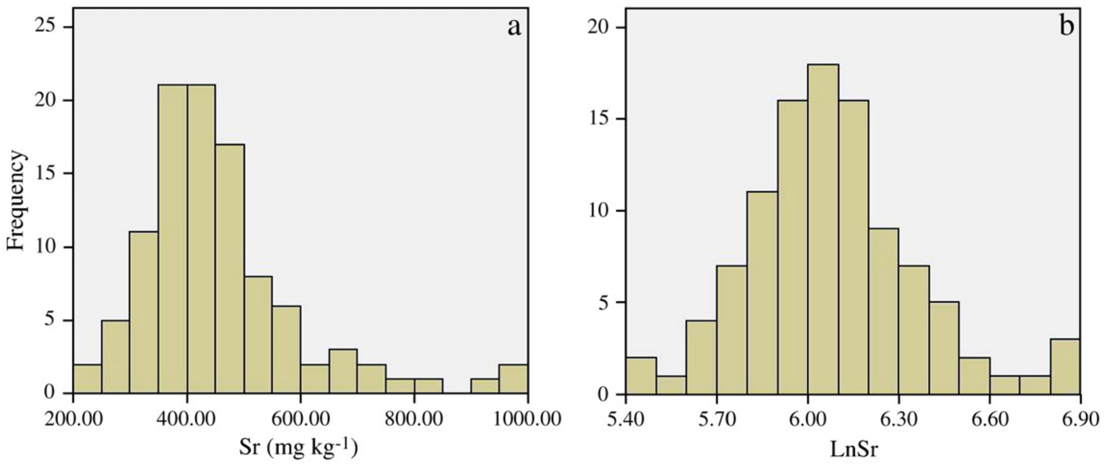

Fig. 2. Distribution of Sr concentration before (a) and after (b) normalization analysis.

Table 2
Correlation coefficient (r) of the element concentrations with soil properties in Isfahan surface soils, central Iran.

	LnPb	LnZn	LnCu	LnBa	LnAs	LnSr	Cd	Mn	V	Cr
Sand	−0.14	−0.15	−0.29**	−0.05	−0.17	−0.37**	−0.03	−0.02	−0.06	−0.31**
Silt	0.14	0.18	0.15	−0.08	−0.07	0.14	−0.08	0.02	0.01	0.28**
Clay	0.145	0.30**	0.23*	−0.02	−0.13	0.39**	−0.00	0.01	0.10	0.21*
EC	0.02[a]	0.03[a]	−0.01[a]	0.06[a]	−0.09[a]	0.11[a]	0.17[a]	−0.08[a]	−0.00[a]	−0.01[a]
pH	0.01	−0.10	−0.07	0.001	0.01	0.03	−0.04	−0.05	−0.02	−0.04
SOM	0.35**	0.41**	0.47**	0.03	0.001	0.27*	0.13	−0.21*	−0.16	0.27*
CCE	0.08	0.05	0.07	0.06	−0.06	0.15	0.17	−0.01	0.05	0.08
CEC	0.05[a]	0.12[a]	0.22*[a]	−0.09[a]	−0.10[a]	−0.17[a]	0.20[a]	−0.25*[a]	0.04[a]	0.23*[a]

Mn: manganese; Sr: strontium; Ba: barium; Cd: cadmium; Pb: lead; Zn: zinc; Cu: copper; As: arsenic; V: vanadium; Cr: chromium; EC: electrical conductivity; pH: soil acidity; SOM: soil organic carbon; CCE: calcium carbonate equivalent; and CEC: cation exchangeable capacity.

[a] Spearman coefficient.

* $P < 0.05$.

** $P < 0.01$.

(40×10^{-8} m^3 kg^1 standard deviation on this mean value?). The average value of magnetic susceptibility (χ) for industrial, roadside, residential, campus and for public parks soil in urban soils of Hangzhou city. The results in this study were similar to the results on soil samples taken from less polluted areas on the campus and in public parks in Hangzhou.

The concentration of pedogenic super paramagnetic (SP) grains in soil is reflected by χfd%. Coarse magnetic particles, such as multi-domain (MD) and stable single domain (SSD) grains of magnetite, show similar susceptibility values at low and high frequencies (Hu et al., 2007). Hu et al. (2007) reported that χfd% for the agricultural and urban topsoils is $<3.6\%$, because they contain little to no SP grains.

The χfd of urban topsoil samples varied from 0.45% to 7.7%, with mean value of 3.96%, which is lower than those found in the natural soils east of Isfahan (Ayoubi et al., 2002), but are similar to the average χfd values in the urban soils. Low mean value of χfd indicates that the topsoil contains grains that are larger than the SP grain size. Correlations between metals and χfd% in topsoils are not significant (Table 4), also implying the low amount of the SP grains. These results are similar to those reported by Hu et al. (2007) who also observed that the correlation between χlf and χfd% of the urban and agricultural topsoils was not significant ($r^2 = 0.018$, $n = 27$), further indicating that the pedogenic SP grains contribute little to the magnetic enhancement of the urban topsoils.

3.5. Associations of heavy metals with magnetic properties

Many studies have reported the strong relationships between χlf and heavy metals in the polluted soils (e.g. D'Emilio et al., 2007; Hu et al., 2007, Lu et al., 2008). To examine the relationships between the heavy metals and mass specific susceptibility, Pearson correlation coefficients were computed (Table 4). Lead, Cu, Zn, and Ba showed strong correlations with magnetic susceptibility, but As, Sr, Cd, Mn, Cr, and V, were not significantly correlated with the magnetic susceptibility (Table 4). Correlations between magnetic susceptibility and heavy metal contents can be used to assess the probable relationship between the magnetic susceptibility and heavy metals. Heavy metal elements may penetrate in the lattice structure of the ferromagnetic materials. They can also be adsorbed by the external surface of ferrimagnetic grains.

Significant correlations have been observed between χlf and heavy metal contents (Zn, Cu, and Pb) in urban soils (Lu and Bai, 2006; Lu et al., 2007; Lu et al., 2008). These three metals show similar chemistry in solute form and have a tendency to co-precipitate with hydrous oxides of Fe and Mn. Generally, magnetic particles of urban topsoils are present as grain sizes are larger than the single domain, which is typical for the anthropogenic origin of heavy metals. Heavy metals can enter urban soils from different sources such as traffic, emissions from industrial plants, burning of fossil fuels and municipal wastes. In particular, Pb, Cu and Zn seem to be mainly associated with traffic, Pb coming from the burning of leaded fuel (until its disappearance and the use of unleaded fuel only), Cu derived from brakes and Zn from tire abrasion. Therefore, a strong correlation of these metals with magnetic susceptibility is expected. (Biasiolia et al., 2006). Scatter plots and linear regression equations of specific susceptibility versus Pb, Cu, Zn and Ba are shown in Fig. 3.

To evaluate the soil environmental quality as affected by the concentrations of heavy metals, PLI was computed in the study area. There was a significant correlation ($r = 0.73$, $p < 0.01$) between PLI and χlf (Fig. 4). These results are consistent with the findings of Lu et al. (2008), who demonstrated significant correlations between PLI and χlf ($r = 0.77$, $p < 0.01$). Wang and Qin (2005) studied urban topsoils of Xuzhou, China and also observed a high correlation between PLI and χlf ($r = 0.78$, $p < 0.0001$). These results provide further evidence that magnetic methods are a good proxy for monitoring and screening the distribution of heavy metal contamination originating from non-point sources of pollution (airborne heavy metals). The basis surrounding the concept is that preferentially adsorption of heavy metals (zinc,

Table 3
Correlation coefficient of the measured heavy metal concentrations in Isfahan city, central Iran.

	LnPb	LnZn	LnCu	LnBa	LnAs	LnSr	Cd	Mn	V	Cr
LnPb	1									
LnZn	0.84**	1								
LnCu	0.72**	0.85**	1							
LnBa	0.35**	0.27**	0.14	1						
LnAs	0.11	0.08	0.15	0.10	1					
LnSr	0.17	0.24*	0.31**	0.10	0.04	1				
Cd	0.38**	0.28**	0.19	0.39**	0.08	0.00	1			
Mn	−0.06	−0.05	0.05	−0.20*	0.21*	0.07	−0.04	1		
V	−0.01	0.07	0.26**	−0.25*	0.24*	−0.09	−0.01	0.48**	1	
Cr	0.20*	0.39**	0.60**	−0.08	0.23*	0.22*	0.15	0.36**	0.74**	1

Mn: manganese; Sr: strontium; Ba: barium; Cd: cadmium; Pb: lead; Zn: zinc; Cu: copper; As: arsenic; V: vanadium; and Cr: chromium.

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

Table 4
Correlation coefficients (r) between heavy metal concentrations and magnetic parameters (χlf and χfd%) in urban soil of Isfahan city, central Iran.

Component	Ln(χlf)	χfd%
Ln(Pb)[a]	0.72^{**}	0.05
Ln(Zn)	0.61^{**}	0.07
Ln(Cu)	0.53^{**}	0.09
Ln(Ba)	0.31^{**}	−0.15
Ln(As)	0.10	0.13
Ln(Sr)	0.18	0.17
Cd	0.15	0.15
Mn	0.16	0.04
V	0.17	0.14
Cr	0.07	0.29^{**}

χlf: low frequency magnetic susceptibility; χfd: frequency-dependent susceptibility Mn: manganese; Sr: strontium; Ba: barium; Cd: cadmium; Pb: lead; Zn: zinc; Cu: copper; As: arsenic; V: vanadium; and Cr: chromium.

[a] Logarithmic values are used for those variables which show lognormal distributions.

** Correlation coefficients are significant at the 0.01 level.

copper, lead and other heavy metals) on external surface of ferromagnetic grains containing notable amounts of Fe oxides provides a rapid and inexpensive assessing of heavy metals in topsoils of urban and industrial areas. Therefore, magnetic mapping can be used as a suitable proxy of expensive and laborious methods of determining heavy metal contamination using the traditional methods of analysis.

The results of multiple linear regression analysis between Ln(χlf) and heavy metal concentrations (since the original data didn't show normal distribution, the natural logarithm of the data used) are presented in Table 5. Stepwise regression analysis of the data was used to determine the priority of heavy metal in the model. The results showed that LnPb, V and LnCu explained the changes in Ln (χlf). About 54% of the metal concentration was explained by the

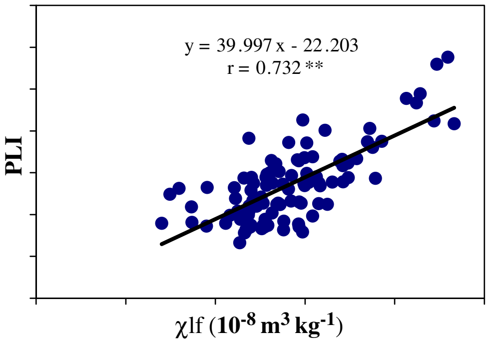

Fig. 4. The scatter plot and regression equation between PLI (Pollution Load Index) and χlf (low frequency magnetic susceptibility) in the study area in central Iran.

variability of magnetic susceptibility (Table 5). LnPb and LnCu were in conformity with correlation data (Table 4) that LnPb, and LnCu had the high correlation coefficients but LnZn was not included in the stepwise regression model (Table 5). This is probably due to the co-linearity and similar sources of Zn and Pb in the study area. Standardized coefficients depicted in Table 5 indicate that LnPb accounts for the major proportion of the changes in magnetic property of χlf (with standardized coefficient of 0.29 compared to s−0.02 and 0.21 for V and LnCu respectively. The stepwise model revealed greater confidence in the prediction of LnPb and V ($P \geq 0.01$) than LnCu ($P \geq 0.05$).

4. Conclusions

The results of this study show that heavy metal concentrations of Pb, Zn, Cu and Ba) are highly correlated with the magnetic susceptibility, whereas those of As, Sr, Cd, Mn, V, Cr show a weak correlation in the topsoils of the urbanized areas. A strong correlation

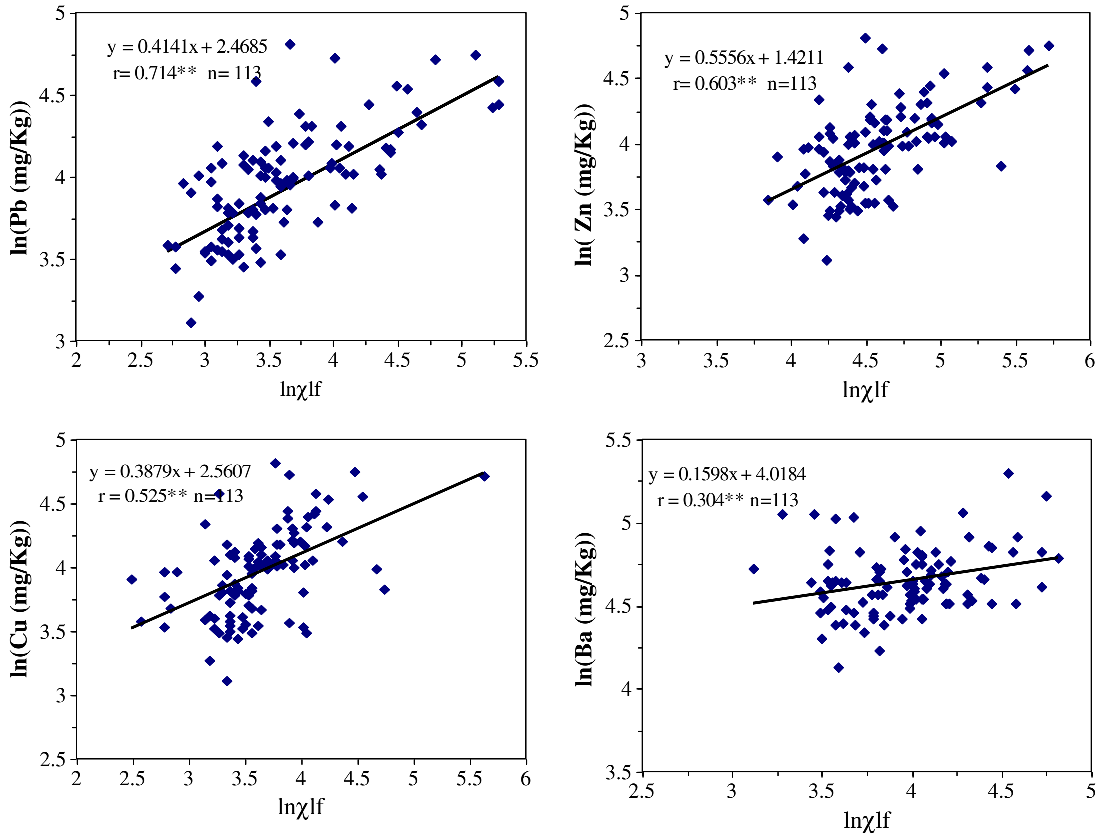

Fig. 3. The scatter plots and linear regression equations of magnetic susceptibility at low frequency (χlf) versus Pb, Zn, Cu, Ba in the studied soils of Isfahan city, central Iran.

Table 5
Multiple regression analysis results between magnetic susceptibility as dependent variable and heavy metal concentrations as independent variables in the study area, central Iran.

Model	Unstandardized coefficients		Standardized coefficients	
	B	Std. Error	Beta	Sig.
(Constant)	2.945	.248		0.001
LnPb	.290	.058	.502	0.001
V	−.020	.005	−.287	0.001
LnCu	.212	.087	.255	0.010
R^2	0.545			

was established between Tomlinson pollution load index (PLI) and the magnetic susceptibility for the polluted samples. There is a linear correlation between magnetic susceptibility and the concentrations of Pb, Zn, Cu, Ba which suggest that the concentration of these heavy metals can be predicted from the magnetic susceptibility. Moreover, the results of multiple linear regression analysis between magnetic susceptibility and heavy metal concentrations indicated that LnPb, V and LnCu could explain approximately 54% of the variability of magnetic susceptibility in the selected area. The results from our study further attest that the measurement of magnetic susceptibility is a simple, rapid, and nondestructive method for the assessment of heavy metal contamination of soils.

References

Angulo, E., 1996. The Tomlinson pollution load index applied to heavy metal "Mussel-Watch" data: a useful index to assess coastal pollution. The Science of the Total Environment 187, 19–56.

Ayoubi, S., Jalalian, A., Karimian Eghbal, M., 2002. Role of pedogenesis in distribution of magnetic susceptibility in two Aridisols from Isfahan, central Iran. In: Angel, Faz, Ortiz, R., Mermut, A.R. (Eds.), International Conference of SUMASS. Spain, pp. 49–50.

Biasiolia, M., Barberisb, R., Ajmone-Marsan, F., 2006. The influence of a large city on some soil properties and metals content. The Science of the Total Environment 356, 154–164.

Chan, L.S., NG, S.L., Davis, A.M., Yim, W.W.S., Yeung, C.H., 2001. Magnetic properties and heavy metal contents of contaminated seabed sediments of Penny's Bay, Hong Kong. Marine Pollution Bulletin 42 (7), 569–583.

Chen, M., Ma, L.Q., Harris, W.G., et al., 1999. Baseline concentrations of 15 trace elements in Florida surface soils. Journal of Environmental Quality 28 (1999), 1173–1181.

Culbard, E.B., Thorntonand, I., Watt, J., 1988. Metal contamination in British urban dusts and soils. Journal of Environmental Quality 17, 226–234.

D'Emilio, M., Chianese, D., Coppola, R., Macchiato, M., Ragosta, M., 2007. Magnetic susceptibility measurements as proxy method to monitor soil pollution: development of experimental protocols for field survey. Environmental Monitoring and Assessment 125, 137–146. doi:10.1007/s10661-006-9246-1.

Freund, R.J., Littell, R.C., 2000. SAS System for Regression. SAS Inst, Cary, NC.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis, In: Klute, A. (Ed.), Methods of Soil Analysis, second ed. : Agron. Monogr., 9. ASA and SSSA, Madison, WI, pp. 383–409. Part 1.

Hanesch, H., Scholger, R., 2002. Mapping of heavy metal loadings in soils by means of magnetic susceptibility measurements. Environmental Geology 42, 857–870.

Hu, X.F., Yu, S., Rong, Y., Li, X.Q., Zhang, G.L., 2007. Magnetic Properties of the Urban Soils in Shanghai and Their Environmental Implications, Catena 70, 428–436.

Lecoanet, H., Leveque, F., Ambrosi, J.P., 2003. Combination of magnetic parameters: an efficient way to discriminate soil-contamination sources (south France). Environmental Pollution 122, 229–234.

Lu, S.G., Bai, S.Q., 2006. Study on the correlation of magnetic properties and heavy metals content in urban soils of Hangzhou City, China. Journal of Applied Geophysics 60, 1–12.

Lu, S.G., Bai, S.Q., Xue, Q.F., 2007. Magnetic properties as indicators of heavy metals pollution in urban topsoils: a case study from the city of Luoyang, China. Geophysical Journal International 171, 568–580.

Lu, S., Wang, H., Bai, S., 2008. Heavy metal contents and magnetic susceptibility of soils along an urban–rural gradient in rapidly growing city of eastern China. Environmental Monitoring and Assessment 155 (1–4), 91–101.

Manta, D.S., Angelone, M., Bellanca, A., Neri, R., Sprovieria, M., 2002. Heavy metals in urban soils: a case study from the city of Palermo (Sicily), Italy. The Science of the Total Environment 300, 229–243.

McLean, E.O., 1982. Soil pH and lime requirement. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. : Part 2, Chemical and Microbiological Properties. American Society of Agronomy, Madison, WI, pp. 199–224.

Mico, C., Recatala, L., Peris, M., Sanchez, J., 2006. Assessing heavy metal sources in agricultural soils of an European Mediterranean area by multivariate analysis. Chemosphere 65, 863–872.

Nan, Z., Zhao, C., Jijun, L., Chen, F., Sun, W., 2002. Relation between soil properties and selected heavy metal concentration in spring wheat (*Triticum aestivum* L.) grown in contaminated soil. Water, Air, and Soil Pollution 133, 205–213.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Part 2. Chemical and Microbiological Properties, Methods of Soil Analysis. ASA, Madison, WI, pp. 539–579.

Rhoades, J.D., 1982. Cation exchange capacity. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Agronomy Monograph, 9. ASA and SSSA, Madison, WI.

Rodríguez Martín, J.A., López Arias, M., GrauCorbí, J.M., 2006. Heavy metals contents in agricultural topsoils in the Ebro basin (Spain). Application of the Multivariate Geostatistical Methods to Study Spatial Variations, Environmental Pollution 144, 101–1012.

J. Rustullet, Estudi de sols fersial. l'ıtics de la serraladalitoralcatalana: Vora NE del Mass'ıs del Garraf, Ph.D. Dissertation, University of Barcelona, 1996.

Sarkar, D., Haldar, A., 2005. Physical and Chemical Methods in Soil Analysis. New Age International, Delhi, India.

Strzyszcz, Z., Magiera, T., 1998. Magnetic susceptibility and heavy metals contamination in soils of Southern Poland. Physics and Chemistry of the Earth 23 (9–10), 1127–1131.

Swan, A.R.H., Sandilands, M., 1995. Introduction to Geological Data Analysis. Blackwell Science, USA.

USDA, 1996. National Soil Survey Handbook, Title 430-VI, Part 647. Soil Survey Staff, Natural Resources Conservation Service, US Department of Agriculture, Government Printing Office, Washington, DC.

Wang, X.S., Qin, Y., 2005. Correlation between magnetic susceptibility and heavy metals in urban topsoil: a case study from the city of Xuzhou, China. Environmental Geology 49, 10–18.