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Using geoaccumulation index to study source profiles of soil dust in China

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Abstract

Source apportionment studies of TSP (atmospheric particulate matter with aerodynamic diameters ⩽100 μm) and PM_{10} (atmospheric particulate matter with aerodynamic diameters ⩽10 μm) have revealed that soil dust is an important source of these particulates in China. In this study, the contamination of soil dust was assessed through the use of a geoaccumulation index (I_{geo}). The mass concentration profiles of 17 elements (Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Ba, and Pb) were established for urban soil dusts. Geochemical compositions of soils from 15 cities were used to represent background urban soil compositions. The results of this study indicated that a number of cities are severely polluted by particulates containing Ca, Cr, Ni, and Cu in both size fractions (TSP and PM_{10}). Contamination with Zn, Pb, Co, and Br was moderate to severe (I_{geo} > 2). The Al and Fe concentrations were not high enough for them to be considered contaminants.

Key words: geoaccumulation index; soil dust; source apportionment; TSP; PM_{10}

Introduction

Many cities in China suffer from high ambient concentrations of atmospheric pollutants, including particulates (TSP and PM_{10}). In 2004, more than 46% of all Chinese cities exceeded the annual average PM_{10} concentrations established in the National Ambient Air Quality Standards (NAAQS). Significant contributors to TSP and PM_{10} are believed to be fugitive dust, soil dust, and coal combustion fly ash (Feng *et al*., 2004, 2005). Soil dust is one of the important sources of TSP and PM_{10} in many cities in China (Zhao *et al*., 2006; Bi *et al*., 2007).

Source apportionment studies of ambient air particles are needed in many Chinese cities. Chemical mass balance (CMB) receptor model (Watson, 1984; Watson *et al*., 2001a), which require information about the chemical characteristics of emission sources, is an important technique for studying ambient air particles. Because soil dust is one of the major sources of TSP and PM_{10}, high quality profile databases for soil dusts are needed. Hundreds of particulate source profiles have been compiled and used in source apportionment studies (Watson *et al*., 2001a), and existing profiles have been used in other studies (Mahmoud *et al*., 2002). Most of the mass of geological material is contained in the coarse portion of PM_{10}, and similar compositions are often found for the $PM_{2.5}$ and PM_{10} size fractions (Chow *et al*., 1994; Watson *et al*., 2001a). Soil dust profiles differ with respect to location and time, and additional profiles are always needed for contemporary inventories and source apportionment studies (Watson *et al*., 2001b). Therefore, factors affecting the soil dust profile deserve further study. Soil dust incorporates or accumulates most pollutants that get into the air. Thus, assessment of the elemental enrichment of soil dusts, especially those influenced by industrial contamination and other anthropogenic activities, is of great importance.

The measurement of elemental soil dust enrichment can be carried out in many ways. The most important methods are the geoaccumulation index, enrichment factor index, and contamination factor index (Loska *et al*., 1997). In this study, the geoaccumulation index was used. This article presents the concentrations of 17 elements in the soil dust of 15 cities located in the east and north-west of China (the cities are: Anyang, Beijing, Handan, Jinan, Shijiazhuang, Tianjin, Yinchuan, Jiaozuo, Taiyuan, Huludao, Shenyang, Urumchi, Zhengzhou, Tangshan, Qinhuangdao). The chemical composition of the size-segregated soil dust has been obtained in China. The majority of the samples in this study were collected for two size fractions (100 μm and 10 μm, respectively).

1 Index of geoaccumulation

The geoaccumulation index (I_{geo}) has been used since the late 1960s, and has been widely employed in European trace metal studies. Originally used for bottom sediments (Müller, 1969), it has been successfully applied to the mea-

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surement of soil contamination (Loska *et al.*, 2003). The I_{geo} enables the assessment of contamination by comparing current and pre-industrial concentrations, although it is not always easy to reach pre-industrial sediment layers. In this study, the I_{geo} for selected soil dusts was calculated using Eq.(1).

$$I_{geo} = \ln \frac{C_n}{1.5 B_n} \quad (1)$$

where, C_n is the measured concentration of the element in soil dust, B_n is the geochemical background value. The constant 1.5 allows us to analyze natural fluctuations in the content of a given substance in the environment and to detect very small anthropogenic influences.

The geoaccumulation index consists of 7 grades or classes (Muller, 1981) (Table 1). Class 6 is an open class and comprises all values of the index higher than class 5. The elemental concentrations in class 6 may be hundred-fold greater than the geochemical background value (Teng *et al.*, 2002).

Table 1 Six classes of the geoaccumulation index

Class	Value	Soil dust quality
0	$I_{geo} \leqslant 0$	Practically uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately to heavily contaminated
4	$3 < I_{geo} < 4$	Heavily contaminated
5	$4 < I_{geo} < 5$	Heavily to extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

2 Materials and methods

2.1 Areas of research

Since 2000, soil dust profiles have been developed for 15 cities in China. In this study, the data of soil dusts from Anyang, Beijing, Handan, Jinan, Shijiazhuang, Tianjin, Yinchuan, Jiaozuo, Taiyuan, Huludao, Shenyang, Urumchi, Zhengzhou, Tangshan, Qinhuangdao were analyzed.

2.2 Sample collection and analytical procedures

A total of at least 1–1.5 kg of soil was collected at each site. Each sample was deposited into a 3.6-L glass jar with a Teflon-sealed lid. A center point for each sampling location was identified using a handheld GPS unit. From the center point, five sub-samples were collected; one at the center point and one each at 100 m north, south, east, and west of the center point. Each sub-sample was collected about 0–20 cm in depth using a flat-bladed shovel, then combined at the center point and thoroughly mixed prior to storage. The soil samples were placed in glass jars and kept frozen at –20°C until they were prepared for analysis. Then the samples were suspended in the resuspension chamber and sampled through PM_{10} and TSP size select cutter on filters for analysis (Chow *et al.*, 1994). The results of this analysis provided the percentage of sand (particles less than 100 μm and particles less than 10 μm in size respectively) (Lowell *et al.*, 2003). X-ray fluorescence spectral 3080 E2 (Rigaku Inc., Japan) was used to analyze 17 elements (Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Ba, and Pb) (Zhao *et al.*, 2006).

Statistical analysis was conducted to eliminate the outliers for each city's data. The individual profiles were further combined to obtain the source profiles used for CMB source apportionment analysis. The simplest composite consisted of the average and standard deviation of species abundances for all individual profiles. The arithmetic mean was calculated to get the soil dust profile of each city. The profiles of 17 elements taken in this study are summarized in Tables 2 and 3.

2.3 Choosing geochemical background values

The B_n parameter in the I_{geo} equation represents the geochemical background value. The equation indicates that the index will be affected by the content of the samples and the geochemical background values. The world average shale (Rubio *et al.*, 2000), the Earth's crust (Loska *et al.*, 2003, 2004), and the world average soil are among the materials most often used to provide background values. However, these levels tend to be very general and may distort the results. Rubio *et al.* (2000) recommended the use of regional background values. While the geochemical background values are constant, the levels of contamination vary with the time and places.

Background values are distinctly different among different soil types, especially with respect to Na, Mg, Al, K, Ca, Ba, Sc, Ti, Fe, and Br (Jiang *et al.*, 1996). For most heavy metals of environmental interest, concentrations in soil easily vary over 2–3 orders of magnitude depending on the parent material from which the soil was derived (Blaser *et al.*, 2000). Therefore, the background geochemical compositions of the city soil types (China National Environmental Monitoring Center, 1990) were chosen as the background values for calculating the I_{geo} values. The data came from the Study of National Soil Environmental Background Values, a research project undertaken during the Seventh Five-Year Plan in China.

The soil compositions were taken from the Atlas of Soil Environmental Background Values (China National Environmental Monitoring Center, 1994). The data in the Atlas included two different layers (layer A and layer C) for the same soil. Layer A was the first layer from the ground which was about 0–20 cm in depth. The data were selected from Layer A because the soil dusts came from the upper layer of the soil. The medians were chosen because some of the data distributions were not normal and the median could show the distributing trend better (Loska *et al.*, 2004). The arithmetic mean of the medians was used for the cities with more than two soil types. Table 4 gives the background soil compositions.

3 Results and discussion

The I_{geo} values for 17 elements for each city are listed in Tables 5 and 6. Applying the classification system devised by Mller (1981) (Table 1), the elements identified in the coarse soil dusts listed in Table 5 may be divided into 4

Table 2 Fine soil dust profiles (diameter ⩽ 10 μm)*, (%)

Cities	Profile ID	Na	Mg	Al	K	Ca	Ti	V	Cr	Mn
Anyang	AnSTC	1.128 (0.953)	1.09 (0.405)	7.403 (0.216)	1.991 (0.061)	3.208 (1.278)	0.39 (0.007)	0.009 (0.003)	0.007 (0.001)	0.054 (0.003)
Handan	HanSTC	0.77 (0.1)	1.36 (0.14)	7.21 (0.2)	2.05 (0.13)	4.34 (0.27)	0.38 (0.01)	0.009 (0.01)	0.006 (0.01)	0.052 (0.01)
Jinan	JiSTC	2.184 (0.805)	1.84 (0.374)	7.3 (1.29)	2.408 (0.853)	3.683 (0.838)	0.576 (0.167)	0.021 (0.003)	0.001 (0.001)	0.106 (0.02)
Jiaozuo	JiaoSTC	0.88 (0.131)	1.32 (1.322)	5.251 (0.295)	1.558 (0.041)	7.142 (1.852)	0.328 (0.023)	0.009 (0.001)	0.005 (0.001)	0.041 (0.004)
Qinhuangdao	QinSTC	1.47 (0.403)	0.54 (0.407)	7.73 (1.01)	2.13 (0.098)	0.76 (0.971)	0.3 (0.094)	0.007 (0.001)	0.007 (0.001)	0.042 (0.006)
Shenyang	ShenSTC	1.4 (0.307)	0.38 (0.502)	4.61 (0.419)	0.97 (0.104)	1.03 (0.837)	0.58 (0.089)	–	0.02 (0.002)	0.02 (0.004)
Shijiazhuang	ShiSTC	1.004 (0.064)	1.25 (0.094)	6.604 (0.266)	1.8 (0.045)	3.402 (0.935)	0.376 (0.014)	0.007 (0.002)	0.007 (0.001)	0.052 (0.004)
Taiyuan	TaiSTC	0.935 (0.137)	1.33 (0.174)	8.15 (0.852)	1.55 (0.12)	6.059 (0.691)	0.404 (0.027)	0.008 (0.005)	0.007 (0.001)	0.057 (0.006)
Tangshan	TangSTC	0.9 (0.376)	0.65 (0.374)	5.65 (0.816)	1.47 (0.134)	0.9 (0.988)	0.36 (0.127)	0.004 (0.001)	0.012 (0.001)	0.022 (0.001)
Tianjin	TianSTC	0.913 (0.472)	0.98 (0.401)	7.56 (1.935)	1.6 (0.598)	3.93 (1.872)	0.38 (0.253)	–	0.005 (0.005)	0.03 (0.007)
Urumchi	UruSTC	0.78 (0.11)	1.08 (0.13)	6.34 (0.33)	1.85 (0.08)	2.99 (0.49)	0.37 (0.07)	0.009 (0.001)	0.005 (0.001)	0.081 (0.01)
Yinchuan	YinSTC	1.18 (0.225)	1.66 (0.319)	5.17 (0.294)	1.79 (0.152)	6.38 (1.163)	0.34 (0.097)	0.009 (0.003)	0.007 (0.003)	0.049 (0.005)
Zhengzhou	ZhengSTC	1.128 (0.953)	1.09 (0.405)	7.403 (0.216)	1.991 (0.061)	3.208 (1.278)	0.39 (0.007)	0.009 (0.003)	0.007 (0.001)	0.054 (0.003)

Cities	Profile ID	Fe	Co	Ni	Cu	Zn	Br	Ba	Pb
Anyang	AnSTC	2.775 (0.856)	0.001 (0.001)	0.003 (0.001)	0.003 (0.001)	0.01 (0.006)	0.0004 (0.003)	0.039 (0.014)	0.004 (0.002)
Handan	HanSTC	3.23 (0.22)	0.001 (0.01)	0.003 (0.01)	0.002 (0.01)	0.007 (0.01)	0.0004 (0.01)	0.046 (0.01)	0.003 (0.01)
Jinan	JiSTC	4.606 (0.885)	–	0.014 (0.004)	0.005 (0.001)	0.007 (0.003)	–	–	0.006 (0.001)
Jiaozuo	JiaoSTC	2.42 (0.179)	0.001 (0.002)	0.002 (0.002)	0.002 (0.002)	0.008 (0.002)	–	0.006 (0.004)	0.004 (0.001)
Qinhuangdao	QinSTC	3.37 (0.378)	–	0.002 (0.002)	0.003 (0.001)	0.007 (0.003)	–	–	0.003 (0.009)
Shenyang	ShenSTC	1.86 (0.543)	–	0.01 (0.001)	0.04 (0.002)	–	–	0.03 (0.001)	–
Shijiazhuang	ShiSTC	2.9 (0.184)	0.001 (0.001)	0.003 (0.001)	0.002 (0.001)	0.008 (0.001)	0.0003 (0.0002)	0.054 (0.003)	0.002 (0.001)
Taiyuan	TaiSTC	3.308 (0.403)	0.001 (0.002)	0.003 (0.001)	0.003 (0.002)	0.008 (0.002)	0.0006 (0.0005)	0.047 (0.004)	0.002 (0.002)
Tangshan	TangSTC	2.0 (0.34)	–	0.005 (0.001)	0.004 (0.001)	0.003 (0.002)	–	–	0.005 (0.003)
Tianjin	TianSTC	1.71 (0.437)	–	0.013 (0.004)	0.007 (0.007)	–	–	0.06 (0.035)	0.005 (0.005)
Urumchi	UruSTC	2.56 (0.17)	0.001 (0.002)	0.003 (0.002)	0.004 (0.002)	0.009 (0.001)	–	0.052 (0.003)	0.002 (0.001)
Yinchuan	YinSTC	2.51 (0.327)	0.001 (0.001)	0.002 (0.002)	–	0.006 (0.002)	–	0.035 (0.008)	0.002 (0.002)
Zhengzhou	ZhengSTC	2.775 (0.856)	0.002 (0.001)	0.003 (0.001)	0.003 (0.001)	0.01 (0.006)	–	–	0.002 (0.001)

* Data within brackets are uncertainties, "–" means the data are undetectable.

groups; practically uncontaminated (class 0), uncontaminated to moderately contaminated (class 1), moderately contaminated (class 2), and heavily contaminated (class 4). The I_{geo} values revealed that nearly all of the profiles for Al, K, Ti, Fe, and Ba fell into class 0 (Fig.1, Table 5). I_{geo} values for Na, Mg, V, Mn, Co, Zn, and Br are > 0 and < 1 for JiSTC, TaiSTC, UruSTC, and ZhengSTC. This indicates that the soil dust in these cities is uncontaminated to moderately contaminated by these elements. The I_{geo} values for Ca, Cr, and Ni in JiSTC, TaiSTC, ShenSTC, and TianSTC are greater than 1 (moderately contaminated).

The Cu I_{geo} values varied the most, ranging from −0.72 to 3.73 (Fig.1). The median I_{geo} for Cu is –0.005, which falls into the category of "practically uncontaminated" (Fig.1), while the maximum geoaccumulation index value of 3.73 suggests the existence of considerable soil contamination in Shenyang. Elevated Cu concentrations are largely the result of the metallurgical industry, bearing and brushing wear, moving engine parts, fungicides and insecticides, corrosion of Cu plumbing, concrete and asphalt, rubber, phosphate fertilizers, and sewage sludges (Sutherland, 2000); hence, concentrations found in Shenyang and

Table 3 Coarse soil dust profiles (diameter ⩽ 100 μm)*, (%)

Cities	Profile ID	Na	Mg	Al	K	Ca	Ti	V	Cr	Mn
Anyang	AnSTF	0.281 (0.075)	1.723 (0.105)	7.404 (0.131)	2.43 (0.095)	5.35 (1.015)	0.491 (0.02)	0.011 (0.01)	0.01 (0.002)	0.076 (0.007)
Beijing	BeiSTF	2.11 (0.06)	2.06 (0.21)	8.87 (0.07)	2.02 (0.025)	5.74 (0.075)	0.14 (0.025)	0.004 (0.003)	0.01 (0.003)	0.145 (0.054)
Handan	HanSTF	0.427 (0.188)	1.641 (0.12)	6.835 (0.121)	2.39 (0.162)	7.025 (1.007)	0.441 (0.013)	0.01 (0.0‘)	0.008 (0.005)	0.071 (0.005)
Huludao	HuSTF	1.074 (0.102)	0.453 (0.104)	10.71 (1.134)	0.689 (0.095)	1.27 (0.499)	0.217 (0.071)	0.019 (0.005)	0.017 (0.003)	0.042 (0.008)
Jinan	JiSTF	1.962 (0.694)	1.88 (0.241)	6.711 (2.065)	1.978 (0.608)	4.312 (1.076)	0.611 (0.051)	0.015 (0.003)	0.062 (0.017)	0.134 (0.049)
Jiaozuo	JiaoSTF	0.458 (0.048)	1.619 (0.128)	6.676 (0.46)	1.94 (0.068)	7.86 (2.026)	0.334 (0.032)	0.01 (0.001)	0.006 (0.001)	0.05 (0.006)
Shenyang	ShenSTF	1.16 (0.125)	0.6 (0.202)	8.24 (0.614)	1.6 (0.512)	2.05 (0.981)	0.97 (0.037)	–	0.02 (0.001)	0.04 (0.004)
Shijiazhuang	ShiSTF	0.754 (0.042)	1.732 (0.096)	7.844 (0.26)	2.097 (0.081)	4.91 (1.949)	0.44 (0.035)	0.011 (0.003)	0.01 (0.001)	0.083 (0.009)
Taiyuan	TaiSTF	0.709 (0.128)	1.643 (0.294)	8.971 (1.219)	1.682 (0.308)	9.119 (2.853)	0.42 (0.045)	0.009 (0.001)	0.01 (0.003)	0.072 (0.009)
Tianjin	TianSTF	1.85 (0.61)	2.05 (0.5)	10.1 (2.94)	3.68 (0.88)	8.54 (3.84)	0.76 (0.26)	–	0.017 (0.021)	0.059 (0.02)
Urumchi	UruSTF	0.31 (0.11)	1.5 (0.07)	6.18 (0.2)	2.21 (0.11)	4.91 (1.1)	0.45 (0.16)	0.01 (0.001)	0.007 (0.001)	0.113 (0.012)
Yinchuan	YinSTF	0.88 (0.185)	2.0 (0.308)	5.75 (0.476)	1.94 (0.317)	9.39 (2.088)	0.36 (0.102)	0.01 (0.003)	0.009 (0.004)	0.062 (0.006)
Zhengzhou	ZhengSTF	1.974 (0.199)	0.95 (0.148)	8.024 (0.518)	2.069 (0.257)	4.198 (0.731)	0.243 (0.131)	0.003 (0.001)	0.01 (0.005)	0.033 (0.01)

Cities	Profile ID	Fe	Co	Ni	Cu	Zn	Br	Ba	Pb
Anyang	AnSTF	4.31 (0.259)	0.002 (0.002)	0.006 (0.001)	0.006 (0.001)	0.021 (0.008)	0.0007 (0.0005)	0.058 (0.003)	0.009 (0.002)
Beijing	BeiSTF	2.22 (0.01)	0.003 (0.001)	0.003 (0.001)	0.03 (0.015)	0.073 (0.008)	–	–	0.017 (0.001)
Handan	HanSTF	4.029 (0.592)	0.004 (0.001)	0.001 (0.001)	0.004 (0.002)	0.013 (0.006)	0.001 (0.001)	0.056 (0.002)	0.004 (0.24)
Huludao	HuSTF	3.68 (0.211)	0.001 (0.001)	0.009 (0.001)	0.004 (0.003)	0.029 (0.026)	–	–	0.003 (0.001)
Jinan	JiSTF	4.65 (0.982)	–	0.032 (0.007)	0.018 (0.007)	0.055 (0.068)	–	–	0.009 (0.001)
Jiaozuo	JiaoSTF	3.247 (0.238)	0.001 (0.003)	0.003 (0.002)	0.004 (0.001)	0.013 (0.002)	0.001 (0.002)	0.042 (0.004)	0.006 (0.001)
Shenyang	ShenSTF	2.03 (0.614)	0.01 (0.003)	0.01 (0.001)	0.01 (0.003)	0.02 (0.005)	–	0.05 (0.003)	–
Shijiazhuang	ShiSTF	4.3 (0.347)	0.002 (0.001)	0.005 (0.002)	0.005 (0.001)	0.013 (0.002)	0.0005 (0.006)	0.064 (0.004)	0.005 (0.002)
Taiyuan	TaiSTF	4.074 (0.397)	0.002 (0.001)	0.005 (0.003)	0.01 (0.003)	0.023 (0.012)	0.0014 (0.001)	0.056 (0.003)	0.01 (0.005)
Tianjin	TianSTF	2.96 (0.17)	0.003 (0.003)	0.018 (0.008)	0.016 (0.007)	0.034 (0.008)	–	0.134 (0.03)	0.01 (0.01)
Urumchi	UruSTF	3.59 (0.25)	0.003 (0.002)	0.004 (0.001)	0.008(0.003)	0.019 (0.01)	0.0005 (0.001)	0.07 (0.005)	0.004 (0.34)
Yinchuan	YinSTF	3.08 (0.333)	0.001 (0.001)	0.005 (0.001)	–	0.017 (0.011)	–	0.043 (0.005)	0.009 (0.639)
Zhengzhou	ZhengSTF	2.062 (0.267)	0.003 (0.001)	0.005 (0.002)	0.029 (0.059)	0.024 (0.037)	–	–	0.003 (0.002)

* Data within brackets are uncertainties, "–" means the data are undetectable.

Zhengzhou have been significantly influenced by anthropogenetic activities.

JiSTC, TaiSTC, TianSTC, ZhengSTC were found to contain similar pollution levels. Their greatest I_{geo} values are > 1 and < 2, indicating that these elements are affected by anthropogenic activities. ShenSTC is notable because of its high I_{geo} for Cu (3.73). Other values are very similar.

As with Table 5, the I_{geo} values in Table 6 can be classified according to the level of contamination (classes 1–4). The I_{geo} values for Al and Fe are mostly negative, indicating a lack of contamination (class 0) (Fig.2). The greatest values for Na, Mg, K, Ti, V, Mn, and Ba are >0 and <1 in some cities (Table 6). Such soils are classified as uncontaminated to moderately contaminated (class 1). The I_{geo} values for Ca are greater than 1 in some cities; their soil dust compositions are rated as being moderately contaminated (class 2). About 35% of the elements examined in this study were found to be at levels classified as moderately to heavily polluted (i.e., I_{geo} 2–3). I_{geo} values for Cr, Co, Ni, Zn, Br, and Pb were found to be in the range of 3. The Cu I_{geo} values ranged from negative up to 3.14, indicating class 3 and class 4 contamination in some cities.

Table 4 Soil background values for layer A (%)

Cities	Na	Mg	Al	K	Ca	Ti	V	Cr	Mn
Anyang	1.40	1.09	6.83	1.98	2.43	0.37	0.008	0.0064	0.0583
Handan	1.40	1.09	6.83	1.98	2.43	0.37	0.008	0.0064	0.0583
Beijing	1.28	0.99	6.83	1.95	1.99	0.38	0.008	0.0064	0.0594
Huludao	1.15	0.88	6.83	1.92	1.54	0.39	0.008	0.0064	0.0604
Shenyang	1.15	0.71	6.59	1.83	0.68	0.40	0.008	0.0058	0.0610
Jinan	1.15	0.80	6.71	1.88	1.11	0.40	0.008	0.0061	0.0607
Jiaozuo	1.40	1.09	6.83	1.98	2.43	0.37	0.008	0.0064	0.0583
Qinhuangdao	1.15	0.88	6.83	1.92	1.54	0.39	0.008	0.00639	0.0604
Shijiazhuang	1.15	0.88	6.83	1.92	1.54	0.39	0.008	0.0064	0.0604
Taiyuan	1.15	0.88	6.83	1.92	1.54	0.39	0.008	0.0064	0.0604
Tangshan	1.15	0.88	6.83	1.92	1.54	0.39	0.008	0.00639	0.0604
Tianjin	1.40	1.09	6.83	1.98	2.43	0.37	0.008	0.0064	0.0583
Urumchi	1.60	0.93	4.75	2.10	1.51	0.33	0.006	0.0045	0.0478
Yinchuan	1.26	1.69	6.11	1.96	4.93	0.30	0.007	0.0054	0.0629
Zhengzhou	1.28	0.99	6.83	1.95	1.99	0.38	0.008	0.0064	0.0594
Cities	Fe	Co	Ni	Cu	Zn	Br	Ba	Pb	
Anyang	3.05	0.0012	0.0027	0.0022	0.0067	0.00030	0.0480	0.0021	
Handan	3.05	0.0012	0.0027	0.0022	0.0067	0.00030	0.0480	0.0021	
Beijing	3.07	0.0012	0.0028	0.0023	0.0067	0.00027	0.0477	0.0020	
Huludao	3.08	0.0013	0.0029	0.0023	0.0068	0.00023	0.0474	0.0020	
Shenyang	2.81	0.0014	0.0025	0.0020	0.0064	0.00031	0.0483	0.0024	
Jinan	2.95	0.0013	0.0027	0.0022	0.0066	0.00027	0.0479	0.0022	
Jiaozuo	3.05	0.0012	0.0027	0.0022	0.0067	0.00030	0.0480	0.0021	
Qinhuangdao	3.08	0.0013	0.00287	0.0023	0.00676	0.000227	0.0474	0.002	
Shijiazhuang	3.08	0.0013	0.0029	0.0023	0.0068	0.00023	0.0474	0.0020	
Taiyuan	3.08	0.0013	0.0029	0.0023	0.0068	0.00023	0.0474	0.0020	
Tangshan	3.08	0.0013	0.00287	0.0023	0.00676	0.000227	0.0474	0.002	
Tianjin	3.05	0.0012	0.0027	0.0022	0.0067	0.00030	0.0480	0.0021	
Urumchi	2.40	0.0011	0.0024	0.0019	0.0055	0.00016	0.0467	0.0019	
Yinchuan	2.86	0.0014	0.0030	0.0026	0.0068	0.00018	0.0473	0.0021	
Zhengzhou	3.07	0.0012	0.0028	0.0023	0.0067	0.00027	0.0477	0.0020	

Table 5 Geoaccumulation index values for elements in coarse soil dust

Profile ID	Na	Mg	Al	K	Ca	Ti	V	Cr	Mn
AnSTC	–0.90	–0.59	–0.47	–0.58	–0.18	–0.51	–0.31	–0.38	–0.71
HanSTC	–1.45	–0.26	–0.51	–0.53	0.25	–0.56	–0.34	–0.62	–0.76
JiSTC	0.34	0.63	–0.46	–0.22	1.15	–0.17	0.82	–3.83	0.22
JiaoSTC	–1.25	–0.31	–0.96	–0.93	0.97	–0.76	–0.37	–0.94	–1.09
QinSTC	–0.23	–1.28	–0.41	–0.44	–1.61	–0.98	–0.76	–0.45	–1.11
ShenSTC	–0.30	–1.49	–1.10	–1.50	0.01	–0.05	–	1.21	–2.19
ShiSTC	–0.78	–0.08	–0.63	–0.68	0.56	–0.64	–0.68	–0.42	–0.80
TaiSTC	–0.88	0.01	–0.33	–0.90	1.39	–0.53	–0.50	-0.40	–0.68
TangSTC	–0.94	–1.02	–0.86	–0.97	–1.36	–0.72	–1.57	0.32	–2.04
TianSTC	–1.20	–0.74	–0.44	–0.89	0.11	–0.55	–	–0.94	–1.54
UruSTC	–1.62	–0.37	–0.17	–0.77	0.40	–0.41	–0.03	–0.38	0.18
YinSTC	–0.68	–0.61	–0.82	–0.71	–0.21	–0.39	–0.20	–0.24	–0.96
ZhengSTC	–0.25	–0.76	–0.38	–0.42	0.34	–1.38	–1.61	0.49	–1.58
Profile ID	Fe	Co	Ni	Cu	Zn	Br	Ba	Pb	
AnSTC	–0.72	–0.80	–0.54	–0.40	–0.04	–0.18	–0.87	0.31	
HanSTC	–0.50	–0.67	–0.52	–0.57	–0.44	–0.18	–0.66	–0.20	
JiSTC	0.06	–	1.70	0.68	–0.48	–	–	0.93	
JiaoSTC	–0.92	–0.80	–1.02	–0.72	–0.32	–	–3.58	0.38	
QinSTC	–0.45	–	–1.11	–0.22	–0.53	–	–	–	
ShenSTC	–1.18	–	1.43	3.73	–	–	–1.27	–	
ShiSTC	–0.67	–0.54	–0.67	–0.57	–0.37	–0.18	–0.40	–0.30	
TaiSTC	–0.48	–0.56	–0.78	–0.20	–0.34	0.82	–0.61	–0.49	
TangSTC	–1.21	–	0.22	0.19	–1.76	–	0.74	–	
TianSTC	–1.42	–	1.62	1.02	–	–	–0.26	0.70	
UruSTC	–0.49	–0.24	–0.48	0.40	0.22	–	–0.43	–0.36	
YinSTC	–0.78	–1.08	–1.00	–	–0.82	–	–1.00	–0.50	
ZhengSTC	–0.93	0.36	0.25	1.30	–0.60	–	–	–0.84	

"–" means the data are undetectable.

Table 6 Geoaccumulation index values for elements in fine soil dust

Profile ID	Na	Mg	Al	K	Ca	Ti	V	Cr	Mn
AnSTC	–2.90	0.08	–0.47	–0.29	0.55	–0.18	–0.09	0.10	–0.21
HanSTC	0.14	0.48	–0.21	–0.54	0.95	–2.08	–1.56	–0.02	0.70
JiSTC	–2.30	0.01	–0.58	–0.31	0.95	–0.33	–0.22	–0.27	–0.30
JiaoSTC	–0.68	–1.54	0.06	–2.06	–0.87	–1.43	0.64	0.85	–1.11
QinSTC	0.19	0.66	–0.58	–0.51	1.37	0.05	0.32	2.78	0.56
ShenSTC	–2.20	–0.01	–0.62	–0.61	1.11	–0.73	–0.22	–0.68	–0.81
ShiSTC	–0.57	–0.83	–0.26	–0.78	1.01	0.69	–	1.21	–1.19
TaiSTC	–1.19	0.39	–0.39	–0.46	1.09	–0.41	–0.17	0.04	–0.13
TangSTC	–1.28	0.32	–0.19	–0.78	1.98	–0.48	–0.40	0.08	–0.33
TianSTC	–0.18	0.33	–0.02	0.31	1.23	0.45	–	0.81	–0.58
UruSTC	–2.94	0.10	–0.21	–0.51	1.12	–0.13	0.18	0.03	0.66
YinSTC	–1.11	–0.35	–0.67	–0.60	0.34	–0.33	–0.09	0.20	–0.61
ZhengSTC	0.05	–0.63	–0.35	–0.50	0.50	–1.22	–1.83	0.07	–1.44

Profile ID	Fe	Co	Ni	Cu	Zn	Br	Ba	Pb
AnSTC	–0.09	–0.12	0.61	0.86	1.07	0.62	–0.31	1.48
HanSTC	–1.05	0.44	–0.74	3.14	2.85	–	–	2.44
JiSTC	–0.18	1.20	–2.02	0.28	0.38	1.14	–0.36	0.38
JiaoSTC	–0.33	–0.70	1.04	0.05	1.50	–	–	0.05
QinSTC	0.07	–	2.99	2.43	2.47	–	–	1.41
ShenSTC	–0.49	–0.80	–0.44	0.28	0.38	1.14	–0.78	0.96
ShiSTC	–1.05	2.30	1.43	1.73	1.06	–	–0.54	–
TaiSTC	–0.10	0.09	0.22	0.35	0.39	0.48	–0.14	0.72
TangSTC	–0.18	–0.15	0.22	1.46	1.15	2.08	–0.34	1.68
TianSTC	–0.63	0.78	2.13	2.28	1.75	–	0.90	1.65
UruSTC	1.02	–0.03	1.51	1.19	1.19	–	0.59	–
YinSTC	–0.48	–0.69	0.02	–	0.72	–	–0.73	1.53
ZhengSTC	–1.16	0.60	0.30	3.07	1.23	–	–	–0.28

"–" means the data are undetectable.

Pb I_{geo} values found indicate low contamination in the soil dust samples, but the maximum values of 2.44 denotes considerable contamination (Fig.2).

Maximum relative contamination levels were recorded in Beijing, which is not surprising since it also posted the highest traffic levels and is considered to be an industrial center with a high population density. Automobile emissions have contributed significant amounts of Pb to the environment. The legacy of automobile pollution remains even though the current contribution of Pb from vehicle emissions is negligible. The high Pb fluxes associated with past emissions have been stored in soils and are now being remobilized by surface erosion processes, contributing to soil dust contamination.

The accumulation of metals in soil is a long-term process and it is difficult to remove these substances in a short period of time. Cr, Co, Cu, and Zn come from industrial emissions and the practice of using mixed sewerage to irrigate croplands. Ca is considered to be the "marker" of construction dust. The I_{geo} values for Ca are mostly above zero, and 54% of the profiles are classified as moderately contaminated (class 2). This indicates that these cities are polluted by the construction and building material industry. The I_{geo} for Ni varied from –2.02 in HanSTF to 2.99 in

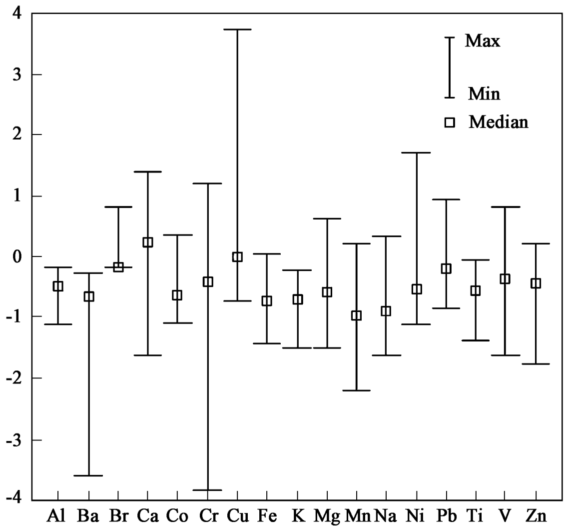

Fig. 1 Geoaccumulation indices (I_{geo}) for elements in soil dusts of TSP in China.

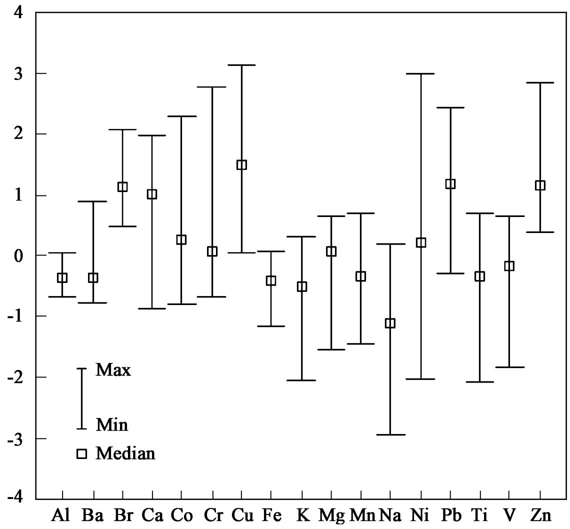

Fig. 2 Geoaccumulation indices for elements in soil dusts of PM_{10} in China.

JiSTF. Sutherland (2000) pointed out that potential anthropogenic sources of Ni include diesel fuel, vehicle exhaust, lubricating oil, metal plating, brushing wear, brake lining wear, asphalt paving, phosphate fertilizers, and storage batteries.

In general, I_{geo} values for fine soil dust showed patterns of contamination similar to those in the coarse fraction. On average, levels of Al and Fe found in this study were well below concentrations deemed polluted. Because they are stable (Schiff *et al.*, 1999; Rubio *et al*., 2000), Al and Fe may be chosen as reference elements for research on soil dust less than 100 μm in diameter. Clear signs of pollution are present for Ca, Cr, Cu, and Ni, with maximum values of I_{geo} close to 4 (Fig.1). The sites at JiSTF, ShenSTF, TaiSTF, BeiSTF, TaiSTF, and ZhengSTF are the areas most contaminated by Ca, Cr, Co, Ni, Zn, Br, and Pb. It should also be noted that the I_{geo} values for Pb and Br in the PM_{10} source profiles are much higher than those in the TSP source profiles. This is most likely due to their originating from automobile exhaust emissions carried in urban runoff. Overall, the elements are more enriched in the fine soil than in the coarse soil.

4 Conclusions

The index of geoaccumulation was used to evaluate the quality of soil dusts from 15 cities in China. Concentrations of Al, K, Ti, Ba, and Fe in the coarse soil fractions were low (practically uncontaminated). Some cities were contaminated with respect to Ca, Cr, Ni, and Cu. Index values were especially high for Cu.

With respect to the fine soil dust fractions, some cities are heavy contaminated with Cr, Co, Ni, Cu, Zn, Br, and Pb. In particular, the I_{geo} for Cu was 3.14 in Beijing. The fine soils were not contaminated with Al and Fe. These two elements are, therefore, suitable to be reference elements in enrichment studies.

The I_{geo} values for the fine soil dusts are generally higher than those for the coarse fractions of a given element and city. Thus, fine soil dusts tend to be more heavily contaminated than the coarse dusts. This pattern is especially notable for Co, Ni, Cu, Zn, Br, and Pb. These results raise concerns regarding the comparison and substitution of profiles. Further research is needed to examine (1) sampling efficiencies; the location of soil dust should be far away from the sources, (2) methods of comparing profiles, and (3) the use of reference elements in enrichment studies.

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