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Identifying sources of soil inorganic pollutants on a regional scale using a multivariate statistical approach: Role of pollutant migration and soil physicochemical properties

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Principal components analysis with Varimax rotation can help identify sources of soil inorganic pollutants but pollutant migration and soil properties can exert important effects.

Abstract

Principal components analysis (PCA) and correlation analysis were used to estimate the contribution of four components related to pollutant sources on the total variation in concentrations of Cu, Zn, Pb, Cd, As, Se, Hg, Fe and Mn in surface soil samples from a valley in east China with numerous copper and zinc smelters. Results indicate that when carrying out source identification of inorganic pollutants their tendency to migrate in soils may result in differences between the pollutant composition of the source and the receptor soil, potentially leading to errors in the characterization of pollutants using multivariate statistics. The stability and potential migration or movement of pollutants in soils must therefore be taken into account. Soil physicochemical properties may offer additional useful information. Two different mechanisms have been hypothesized for correlations between soil heavy metal concentrations and soil organic matter content and these may be helpful in interpreting the statistical analysis.

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Keywords: Principal components analysis; Varimax rotation; Heavy metal migration; Soil texture; Soil pH

1. Introduction

The anthropogenic impact on the cycling of heavy metals has been important since the Roman period (Rosman et al., 1997). In the last 150 years higher loadings of heavy metals to soils have become more prevalent, mainly due to contamination from metallurgical plants, waste disposal, heating processes and agricultural treatments. Non-ferrous metallurgical activities producing gaseous and particulate matter emissions,

and wastewater and biosolids wastes, have had a severe impact on the natural environment (Dudka and Adriano, 1997). Identifying the sources of heavy metals in the environment is of key importance to our understanding of their pollution patterns and natural cycles in surface reservoirs of the Earth (Cloquet et al., 2006) and for making decisions concerning site remediation.

Methods for source identification and source apportionment were originally developed in studies of air pollution, at first using dispersion models. Later on, because of the limitations of dispersion models there has been increasing interest in, and study of, receptor models which assess the contributions from various sources based on observations at sampling sites,

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the so-called “receptors” (Gordon, 1980). Up to now various methods of studying receptors such as chemical mass balance models, multivariate models and isotope techniques have been used. However, according to Simeonov et al. (2005), the pollution process is in principle a multivariate one and therefore only multivariate treatment of data is appropriate for site assessment. Besides, if the investigator has a general idea of the expected sources of pollutants, multivariate methods can provide some source resolution even when accurate source composition data are lacking. This characteristic is the major strength of multivariate techniques compared with other receptor models.

Around the 1980s soil scientists began to study sources of soil pollutants using methodology developed by atmospheric scientists with virtually no modifications. Because of their advantages mentioned above, PCA and other related multivariate techniques such as factor analysis (FA) and absolute principal components scores (APCS) have been the most widely used methods for identification of pollution sources and apportionment of natural *versus* anthropogenic contributions to soils (Facchinelli et al., 2001; Tariq et al., 2005; Weiss et al., 1994).

The soil is a three-dimensional natural body composed of minerals, organic matter, liquids, and gases and can be regarded as an amalgam of the lithosphere, the biosphere, the hydrosphere and the atmosphere. There are many processes by which materials are exchanged between the soil and the other components of the environment. Thus, there is simultaneous movement of substances into and out of the soil. Soil exchange processes can be much more complicated than those within the atmosphere and this raises an important question: are the methods initially developed for air pollution studies applicable to soil? This is a question that has not yet been adequately addressed.

The present study was therefore carried out on a sub-regional scale in a valley in east China with a history of pyro-metallurgic activities and a number of clearly identifiable potential sources of soil pollutants. The aim was to examine the possible problems involved in source identification of soil inorganic pollutants using a multivariate statistical approach. PCA analysis of a dataset of soil heavy metal concentrations was conducted in an attempt to identify the most important sources of contamination.

2. Materials and methods

2.1. Sampling area

The experimental area was Fuyang valley in Zhejiang Province, east China, a valley 10.9 km² in area with intensive copper and zinc smelting activity since 1950 using traditional techniques. The climate is subtropical with an annual average rainfall of 1442 mm and air temperature of 16.1 °C. The soils are stagnic anthrosols and agri-udic ferrosols. The sampling area was a valley surrounded by low hills and with most of the land used for the cultivation of rice. Other studies have demonstrated that landscape features have a substantial influence on the fate of pollutants in the environment and their spatial distribution in the soils (Zhang et al., 2006).

There were 15 copper- and zinc-smelting furnaces using pyro-metallurgic processes in the valley and the positions of the 9 main factories in the study area are shown in Fig. 1. In order to minimize production costs, mine tailings

Fig. 1. Distribution of copper and zinc smelters in Fuyang valley, Zhejiang province, east China.

or components of waste electronic and electric equipment imported from all over the world have been used as raw materials. The main products are crude copper and zinc. Because the factories have no equipment for dust removal or safe work practices, large quantities of metals have been emitted to the atmosphere in the form of dust and then deposited on to soils and surface waters. Previous studies on Fuyang valley have focused on potential hazards posed by the inorganic pollutants Cu, Zn, Pb, Cd, As, Se, and Hg (Yao et al., 2006) and by polyaromatic hydrocarbons (PAHs) (Xing et al., 2006) in soils resulting from copper and zinc smelting activities and other related processes and have indicated serious contamination of the soils by heavy metal(loid)s.

2.2. Sampling and analysis

Soil sampling was carried out in July 2003. The study area was divided into a grid of 174 square cells using a systematic grid sampling method with regularly spaced intervals of about 250 × 250 m. Within each grid cell five samples were randomly collected to a depth of 0–15 cm and then mixed thoroughly to give a composite sample. The sampling protocol was therefore a combination of systematic grid, simple random and composite sampling methods.

After air-drying, mixing and milling, soil sub-samples were digested with aqua-regia (4:1 HCl/HNO₃ by volume) according to McGrath and Cunliffe (1985) to determine the concentrations of Cu, Zn, Pb, Cd, Fe and Mn. The total concentrations in the solution of Cu, Zn, Pb, Fe and Mn were determined by flame atomic absorption spectrophotometry (Varian SpectraAA 220 FS) and of Cd with a Varian SpectraAA 220Z spectrophotometer using a graphite furnace. Special measures were taken in the determination of Fe because of its relatively

high concentrations in the soils. The burner of the Varian SpectrAA 220 FS was rotated about 45° to the light axis in order to shorten effective path length and therefore to lower the sensitivity. In this way the dynamic range of the equipment was extended (Zhao and Gan, 1998). Results indicated that the method was suitable for the determination of soil Fe and Mn (data not shown).

Soil sub-samples were digested with HNO₃ and HClO₄ for determination of the metalloid As and the non-metal Se, and with HNO₃ and H₂O₂ for the metal Hg. The concentrations of these three elements in the solutions were determined by hydride generation-atomic fluorescence spectrometry (Titan AFS 930). Quality control was based on the combined use of the GSS series of Chinese standard soil reference materials (Geological Standard Research Group, 1987) with internal control samples and duplicate analyses of each sample.

Selected soil physicochemical properties, namely pH, mechanical composition, and organic matter content were also measured. These data and heavy metal concentrations have been discussed elsewhere (Li, 2006; Zhang et al., 2006). Results from the statistical and geostatistical analysis of the data are presented below.

2.3. Statistical analysis

Soil heavy metal and Se concentration data were analyzed by PCA and correlation analysis using version 11.5 of the SPSS software package (SPSS Inc., Chicago, IL). In the PCA, Varimax which was proposed by Kaiser (1958) was used as the rotation method in the analysis following standardization of the data. In Varimax, the simplicity of a factor is defined as the variance of its squared loadings, so when the variance is at a maximum the factor has the greatest interpretability or simplicity in the sense that its components tend towards unity and zero. The criterion of maximum simplicity of a complete factor matrix is defined as the maximization of the sum of these simplicities of the individual factors. Thus Varimax rotation is a rigid, orthogonal rotation of the original components to maximize their alignment with the original variables. Pearson's correlation coefficients were obtained using the BIVARIATE procedure in SPSS.

3. Results and discussion

The component pattern matrix yielded by Varimax rotated PCA is presented in Table 1. Four principal components (Factors 1–4 presented below) were identified and considered, accounting for 90% of the total variance in the dataset. Adding more factors to the model did not markedly increase the percentage of the variation accounted for.

3.1. Factor 1

The first component, which explains 53.1% of the total variance, appears to represent an “anthropogenic factor”, since it

is strongly correlated with the elements Cu, Zn, Pb, and Cd, and to a lesser extent with As, Fe, Mn, Se and Hg. Although the predominant products of smelting were crude Cu and Zn, other elements may have been produced in large quantities as co-products. Lead and Zn are often found together in ore deposits and other materials used for smelting. Due to the high volatility of its compounds when heated to near their boiling points during smelting, lead will be evaporated and oxidized to form oxide fumes or concentrated upon dust surfaces (Barcan, 2002; Eatough et al., 1979; Page et al., 1979) and will then reach soils by aerial deposition.

As, Cd and Hg usually coexist with Cu and Zn and are readily vaporized in the process of smelting (Dudka and Adriano, 1997). It may be argued that this factor represents the effects of the pollution caused by the processing of the raw materials during smelting and may therefore be referred to as a “smelting” factor.

3.2. Factor 2

The second component in Table 1 is most dependent upon Hg, As and Cu and accounts for about 13.9% of the total variance. Factor 2 appears to be related to another “anthropogenic factor”, which is consistent with the results of previous studies (Zhang et al., 2006).

Mercury is generally regarded as a tracer element for coal combustion and both smelting and coal combustion can emit large amounts of As (Keegan et al., 2006; Wang and Mulligan, 2006) and Hg (Feng et al., 2005; Pacyna et al., 2006; Streets et al., 2005; Wong et al., 2006), which may explain the apparent close association between these processes as sources of these elements in the study area. As would be expected, smelting furnaces and coal combustion furnaces are situated close to each other and therefore geostatistics and GIS cannot distinguish between their individual effects on soil pollutants. The exact sources of As and Hg are still not fully understood and require further investigation.

Much of the organic matter and various elements produced by coal burning are released to the atmosphere in gaseous forms or as fly ash which reaches the soils by aerial deposition. Coal burning would therefore be expected to increase the organic matter content of the surrounding soils (Gonzalez-Perez et al., 2004; Sajwan et al., 2006). If coal burning processes had such a large effect that the contribution of the soil parent material could be ignored, there might be some positive relationship between soil Hg and organic matter content, reflecting their relationship with the quantity of the emissions. Soil organic matter would then provide useful information on the source identification of this component. There was no significant relationship between Hg or As concentration and soil organic matter content across all the 174 samples as shown in Table 2. However, kriging maps for Hg and organic matter, with the methodology presented by Zhang et al. (2006), showed similar spatial distributions (Fig. 2), indicating a certain relationship between them. Previous results obtained from this area showed that Hg and especially organic matter in some samples were not adversely affected by anthropogenic

Table 1
Component pattern matrix for Varimax rotated PCA analysis of all 174 soil samples

Element	PC1	PC2	PC3	PC4
Cu	0.712	0.607	0.306	0.085 a tracer element
Zn	0.963	0.137	0.147	0.041
Pb	0.935	0.250	0.111	0.127
Cd	0.563	0.159	0.716	−0.032
Fe	0.451	0.259	−0.107	0.584
Mn	−0.033	−0.043	0.086	0.925
As	0.485	0.815	0.213	0.143
Se	0.039	0.159	0.931	0.051
Hg	0.103	0.976	0.113	−0.009
Explained variance in %	53.1	13.9	11.7	11.2

Table 2
Correlation coefficients (*r*) between metal concentrations and soil physicochemical properties of all 174 soil samples collected

Property	Cu	Zn	Pb	Cd	Fe	Mn	As	Se	Hg
Clay	−0.036	−0.008	−0.001	−0.003	0.153*	0.079	−0.013	0.060	−0.079
OM	0.087	0.085	0.043	0.287**	−0.327**	−0.115	−0.004	0.227**	0.014

***r* is significant at the 0.01 level (two-tailed test); **r* is significant at the 0.05 level (two-tailed test).

activities. Therefore, statistical analysis using all 174 samples from the area would, to some extent, underestimate any correlation between Hg and organic matter emission. We therefore selected the 51 most contaminated samples and repeated the correlation analysis using this smaller dataset. Using the smaller dataset soil Hg, As and Cu concentrations were positively related to soil organic matter content (Table 3). Thus, it appears that Hg and organic matter are derived mainly from the same source and it may be suggested that the second component represents a “coal combustion” factor.

According to the literature, coal is not rich in Cu, but PCA analysis reveals that considerable amounts of Cu are emitted in the combustion process. There may have been a reaction between Cu and other combustion by-products during the smelting process which made Cu appear to be a product of combustion, but elucidation of this requires further study.

3.3. Factor 3

The third component is mainly composed of Se and Cd, but it is complex and difficult to explain. According to previous studies, Se and Cd concentrations in soils are controlled

by smelting activities and the location of the highest concentrations coincides closely with that of the smelting furnaces from which soil concentrations of Se and Cd decreased with increasing distance (Zhang et al., 2006). Numerous studies have indicated that metal smelting was the main source of atmospheric emissions of Se and Cd which then polluted the surrounding soils (Dudka et al., 1995; Dudka and Adriano, 1997). These two elements were thought to be grouped with other elements emitted by the smelting furnaces and contained in the first component. However, the statistical analysis of the results was not consistent with our assumption. We therefore hypothesized that there must be a certain property differentiating the two elements from those correlated with the first component in the PCA. Furthermore, soil Se and Cd concentrations are significantly and positively correlated with soil organic matter content (Table 2) in contrast to the other elements studied.

Once in the soil, Se undergoes relatively rapid physicochemical transformations under the influence of oxidation-reduction and biological activity. The formation of selenides (H_2Se), more mobile forms than the selenates and selenites, is facilitated under reductive conditions. Long-term water-logged conditions result in the depletion of molecular oxygen

Fig. 2. Maps of kriging estimates for soil Hg and soil organic matter in Fuyang valley.

Table 3

Correlation coefficients (*r*) between metal concentrations and soil physicochemical properties of the 51 most polluted soil samples collected

Property	Cu	Zn	Pb	Cd	Fe	Mn	As	Se	Hg
Clay	−0.314*	−0.291*	−0.228	−0.133	−0.078	0.066	−0.052	−0.101	−0.093
OM	0.353*	−0.083	−0.158	0.446**	−0.524**	−0.056	0.353*	0.569**	0.375**

***r* is significant at the 0.01 level (two-tailed test); **r* is significant at the 0.05 level (two-tailed test).

and a decrease in redox potential (Eh) in stagnic anthrosols (paddy soils), which will facilitate the formation of elemental Se (Cao et al., 2001) and even selenides (Xiong et al., 1999). In an anionic form (selenates, selenites, selenides) or organo-mineral form (methyl-Se), Se is retained to a lesser extent in the solid phase of the soil than the other contaminants, which are for the most part cationic, and Se therefore migrates to some extent from the surface horizon. Selenium contamination was found to a depth of about 1 m, with sigmoid profiles which showed a maximum concentration at a depth of 0.7 m (Sterckeman et al., 2002). The remaining Se in soil generally strongly associates with the soil organic matter (Sterckeman et al., 2002), and this may explain the positive relationship between Se and organic matter contents in the surface soils.

Cadmium is more mobile in soil than most other heavy metals (Autier and White, 2004). Under the same soil conditions the mobility of Cd, Cu and Zn can be ranked in the following order: Cd > Pb ≥ Zn (Sterckeman et al., 2000). The mobility of Cd seems to be facilitated at low pH. In the study area there were 33 samples with a pH value less than 5.0, accounting for about 19% of the total samples that were taken. The relatively low pH of these soils may promote the mobility of Cd.

Studies have shown that the association of Cd with the soil clay mineral fraction was clearly less strong than binding to organic matter (Janssen et al., 1997; Prokop et al., 2003; Sterckeman et al., 2004). Lee et al. (1996) pointed out that the facial adsorption sites for Cd were principally composed of organic matter and concluded that besides pH, organic matter content was the most influential soil characteristic for Cd partitioning. Results from the present study are in agreement with this, with a positive relationship between Cd and organic matter content in the surface soils.

From the discussion above, the characteristics of Se and Cd that differentiate them from other elements represented by the first component (Factor 1) can be readily identified: their mobility or tendency to migrate and their high capacity to bind to organic matter. This explanation is consistent with the methods used in the present study. The foundation of receptor-based models for source assignment (including PCA) is a simple mass conservation argument. It is assumed that there is no interaction between the substances that cause mass removal or formation (Henry et al., 1984). There is no modification of the composition between the source and the receptor (Gordon, 1980). However, after entering the soil by aerial deposition (Manceau et al., 2000) or other pathways (Payne et al., 1988), heavy metals interact with phyllosilicates, Fe and Mn oxides, organic matter and other soil components and then participate in various processes including leaching.

All these processes are controlled by the pollutant properties (Hellweg et al., 2005) together with the transport velocity of heavy metals in soils. Different pollutants have different properties and different migration tendencies and therefore after a long period there may be significant differences between the pollutant composition of the source and the receptor so that pollutants from the same source may be partitioned into different factors in PCA and this may lead to errors in the identification of the sources.

Thus, the third component can be regarded as an integrated factor influenced by the “input factors” (the first component) and “output factors”. Unfortunately, subsurface soil samples were not taken from the experimental area, therefore vertical distribution and mobility of the inorganic pollutants in the soils cannot be evaluated.

3.4. Factor 4

The fourth component in Table 1 consists mainly of Fe and Mn. Iron and Mn are two of the most common reference elements when calculating the enrichment factor of soil heavy metal pollutants because they are commonly affected only slightly or remain unaffected in soils (Liu et al., 2005; Quevauviller et al., 1989). Very high loadings of Fe and Mn strongly relate this factor to “soil parent material”. As clay contents have not been markedly changed by anthropogenic activities, the observation that Fe showed a positive correlation with the clay content for 174 samples as shown in Table 2 also indicates that soil Fe concentration is influenced by the parent material (Wilcke et al., 1998). This conclusion is also consistent with the geostatistical results (data not shown).

The concentrations of the nine inorganic pollutants and organic matter in soil are the result of both natural and anthropogenic influences. However, in the study area a considerable body of information indicates that smelting and related processes such as coal combustion are the most important sources of Cu, Zn, Pb, Cd, As, Se, Hg and organic matter, and this was the prerequisite for examining the relationship between Hg and organic matter emissions. No attempt was therefore made to take account of background concentrations in soil. However, it was necessary to determine background concentrations of Fe and Mn because these were the tracer elements for soil parent material in this study.

There are two possible mechanisms that may account for the correlation between inorganic pollutant concentrations and soil organic matter content. For Se and Cd, the correlation is controlled by their affinity to soil organic matter, and the affinity existed for not only the 51 most polluted samples selected from the total but all of the samples taken from the

area. In the case of Hg and As, the correlation is an expression of the coexistence of the two elements and organic matter in fly ash and other coal combustion by-products. This coexistence only affects receptor soils which are contaminated by products of combustion, not all samples collected. Hg and As therefore did not exhibit significant positive correlations with soil organic matter over the total of 174 samples, although they did show some affinity with soil organic matter. This hypothesis can readily explain the results discussed above and may perhaps apply also to organic soil pollutants.

4. Conclusions

PCA analysis of nine inorganic pollutants identified four main components explaining pollutant concentrations in surface soils. Smelting was the most important source of Cu, Zn, Pb, Cd, and Se, while coal combustion was more important for As and Hg. Iron and Mn were controlled by soil parent material. The PCA component pattern matrix indicates some kind of reaction between Cu and coal combustion by-products, but further investigation is needed to elucidate this.

Different pollutants had different tendencies to migrate in soils, potentially leading to significant differences between the pollutant composition of sources and the receptor (the soils), which might lead to misidentification of the sources of pollutants by multivariate statistics. When identifying the sources of soil pollutants, special consideration must therefore be given to both the stability of the pollutants and their migration or movement in soils. The migration of Se and Cd down the soil profile serves as a reminder that it is not sufficient to analyze the surface horizon of a soil in order to assess contamination and source identification.

Soil physicochemical properties are very important for source identification of soil pollutants because they can greatly affect the fate of pollutants in the environment. There may be two different mechanisms for the correlation between soil heavy metal concentrations and soil organic matter content, adsorption affinity to soil organic matter and the coexistence of the heavy metals and organic matter in anthropogenic inputs to soils.

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References

Autier, V., White, D., 2004. Examination of cadmium sorption characteristics for a boreal soil near Fairbanks, Alaska. *Journal of Hazardous Materials* 106, 149–155.

Barcan, V., 2002. Nature and origin of multicomponent aerial emissions of the copper-nickel smelter complex. *Environment International* 28, 451–456.

Cao, Z.H., Wang, X.C., Yao, D.H., Zhang, X.L., Wong, M.H., 2001. Selenium geochemistry of paddy soils in Yangtze River Delta. *Environment International* 26, 335–339.

Cloquet, C., Carignan, J., Libourel, G., Sterckeman, T., Perdrix, E., 2006. Tracing source pollution in soils using cadmium and lead isotopes. *Environmental Science and Technology* 40, 2525–2530.

Dudka, S., Adriano, D.C., 1997. Environmental impacts of metal ore mining and processing: A review. *Journal of Environmental Quality* 26, 590–602.

Dudka, S., Piotrowska, M., Chlopecka, A., Witek, T., 1995. Trace metal contamination of soils and crop plants by the mining and smelting industry in Upper Silesia, South Poland. *Journal of Geochemical Exploration* 52, 237–250.

Eatough, D.J., Eatough, N.L., Hill, M.W., Mangelson, N.F., Ryder, J., Hansen, L.D., Meisenheimer, R.G., Fischer, J.W., 1979. The chemical composition of smelter flue dusts. *Atmospheric Environment* 13, 489–506.

Facchinelli, A., Sacchi, E., Mallen, L., 2001. Multivariate statistical and GIS-based approach to identify heavy metal sources in soils. *Environmental Pollution* 114, 313–324.

Feng, X.B., Li, G.H., Qiu, G.L., 2005. A preliminary study on mercury contamination to the environment from artisanal zinc smelting using indigenous methods in Hezhang County, Guizhou, China: Part 2. Mercury contaminations to soil and crop. *Science of the Total Environment* 368, 47–55.

Geological Standard Research Group, 1987. Geological Standard Reference Samples (in Chinese). Geological Publishing House, Beijing, China.

Gonzalez-Perez, J.A., Gonzalez-Vila, F.J., Almendros, G., Knicker, H., 2004. The effect of fire on soil organic matter—a review. *Environment International* 30, 855–870.

Gordon, G.E., 1980. Receptor models. *Environmental Science and Technology* 14, 792–800.

Hellweg, S., Fischer, U., Hofstetter, T.B., Hungerbühler, K., 2005. Site-dependent fate assessment in LCA: Transport of heavy metals in soil. *Journal of Cleaner Production* 13, 341–361.

Henry, R.C., Lewis, C.W., Hopke, P.K., Williamson, H.J., 1984. Review of receptor model fundamentals. *Atmospheric Environment* 18, 1507–1515.

Janssen, R.P.T., Peijnenburg, W.J.G., Postuma, L., Van Den Hoop, M.A.G.T., 1997. Equilibrium partitioning of heavy metals in Dutch field soils. I. Relationship between heavy metal partition coefficients and soil characteristics. *Environmental Toxicology and Chemistry* 16, 2470–2478.

Kaiser, H.F., 1958. The varimax criterion for analytic rotation in factor analysis. *Psychometrika* 23, 187–200.

Keegan, T.J., Farago, M.E., Thornton, I., Hong, B., Colville, R.N., Pesch, B., Jakubis, P., Nieuwenhuijsen, W., 2006. Dispersion of As and selected heavy metals around a coal-burning power station in central Slovakia. *Science of the Total Environment* 358, 61–71.

Lee, S.-Z., Allen, H.E., Huang, C.P., Sparks, D.L., Sanders, P.F., Peijnenburg, W.J.G.M., 1996. Predicting soil-water partition coefficients for cadmium. *Environmental Science and Technology* 30, 3418–3424.

Li, Z.B., 2006. Distribution characteristic, partitioning model and risk assessment of soil metals in the Yangze River Delta. PhD dissertation. Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China.

Liu, W.H., Zhao, J.Z., Ouyang, Z.Y., Soderlund, L., Liu, G.H., 2005. Impacts of sewage irrigation on heavy metal distribution and contamination in Beijing, China. *Environment International* 31, 805–812.

Manceau, A., Lanson, B., Schlegel, M.L., Harge, J.C., Musso, M., Eybert-Berard, L., Hazemann, J.L., Chateigner, D., Lambelle, G.M., 2000. Quantitative Zn speciation in smelter-contaminated soils by EXAFS spectroscopy. *American Journal of Science* 300, 289–343.

McGrath, S.P., Cunliffe, C.H., 1985. A simplified method for the extraction of the metals Fe, Zn, Cu, Ni, Cd, Pb, Cr, Co and Mn from soils and sewage sludges. *Journal of the Science of Food and Agriculture* 36, 794–798.

Pacyna, E.G., Pacyna, J.M., Steenhuisen, F., Wilson, S., 2006. Global anthropogenic mercury emission inventory for 2000. *Atmospheric Environment* 40, 4048–4063.

Page, A.L., Elseewi, A.A., Straughan, I., 1979. Physical and chemical properties of fly ash from coal-fired power plants with references to environmental impacts. *Residue Reviews* 71, 83–120.

Payne, G.G., Martens, D.C., Kornegay, E.T., Lindemann, M.D., 1988. Availability and form of copper in three soils following eight annual

- applications of copper-enriched swine manure. *Journal of Environmental Quality* 17, 740–746.
- Prokop, Z., Cupr, P., Zlevorova-Zlamalikova, V., Komarek, J., Dusek, L., Holoubek, I., 2003. Mobility, bioavailability, and toxic effects of cadmium in soil samples. *Environmental Research* 91, 119–126.
- Quevauviller, P., Lavigne, R., Cortez, L., 1989. Impact of industrial and mine drainage wastes on the heavy metal distribution in the drainage basin and estuary of the Sado River (Portugal). *Environmental Pollution* 59, 267–286.
- Rosman, K.J.R., Chisholm, W., Hong, S.M., Candelone, J.P., Boutron, C.F., 1997. Lead from Carthaginian and Roman Spanish mines isotopically identified in Greenland ice dated from 600 BC to 300 AD. *Environmental Science and Technology* 31, 3413–3416.
- Sajwan, K.S., Punshon, T., Seaman, J.C., 2006. Production of coal combustion products and their potential uses. In: Sajwan, K.S., Twardowska, I., Punshon, T., Alva, A.K. (Eds.), *Coal Combustion Byproducts and Environmental Issues*. Springer, New York, pp. 3–9.
- Simeonov, V., Einax, J., Tsakovski, S., Kraft, J., 2005. Multivariate statistical assessment of polluted soils. *Central European Journal of Chemistry* 3, 1–9.
- Sterckeman, T., Douay, F., Proix, N., Fourrier, H., 2000. Vertical distribution of Cd, Pb and Zn in soils near smelters in the North of France. *Environmental Pollution* 107, 377–389.
- Sterckeman, T., Douay, F., Proix, N., Fourrier, H., Perdrix, E., 2002. Assessment of the contamination of cultivated soils by eighteen trace elements around smelters in the North of France. *Water, Air, and Soil Pollution* 135, 173–194.
- Sterckeman, T., Douay, F., Baize, D., Fourrier, H., Proix, N., Schvartz, C., 2004. Factors affecting trace element concentrations in soils developed on recent marine deposits from northern France. *Applied Geochemistry* 19, 89–103.
- Streets, D.G., Hao, J.M., Wu, Y., Jiang, J.K., Chan, M., Tian, H.Z., Feng, X.B., 2005. Anthropogenic mercury emissions in China. *Atmospheric Environment* 39, 7789–7806.
- Tariq, S.R., Shah, M.H., Shaheen, N., Khalique, A., Manzoor, S., Jaffar, M., 2005. Multivariate analysis of selected metals in tannery effluents and related soil. *Journal of Hazardous Materials* 122, 17–22.
- Wang, S.L., Mulligan, C.N., 2006. Occurrence of arsenic contamination in Canada: Sources, behavior and distribution. *Science of the Total Environment* 366, 701–721.
- Weiss, P., Riss, A., Gschmeidler, E., Schentz, H., 1994. Investigation of heavy metal, PAH, PCB patterns and PCDD/F profiles of soil samples from an industrialized urban area (Linz, Upper Austria) with multivariate statistical methods. *Chemosphere* 29, 2223–2236.
- Wilcke, W., Müller, S., Kanchanakool, N., Zech, W., 1998. Urban soil contamination in Bangkok: heavy metal and aluminium partitioning in topsoils. *Geoderma* 86, 211–228.
- Wong, C.S.C., Duzgoren-Aydin, N.S., Aydin, A., Wong, M.H., 2006. Sources and trends of environmental mercury emissions in Asia. *Science of the Total Environment* 368, 649–662.
- Xing, W.Q., Luo, Y.M., Wu, L.H., Song, J., Qian, W., Christie, P., 2006. Spatial distribution of PAHs in a contaminated valley in Southeast China. *Environmental Geochemistry and Health* 28, 89–96.
- Xiong, Y.F., Li, H.Y., Liu, J.G., Liu, C.M., 1999. Study on valence state transformation and solubility of selenium in paddy soils. *Environmental Chemistry (in Chinese)* 18, 338–343.
- Yao, C.X., Yin, X.B., Zhang, C.B., Luo, Y.M., Li, Z.B., Song, J., 2006. An investigation on arsenic and selenium in paddy soils-rice system in the vicinity of a metal smelter in Zhejiang province. *Soils (in Chinese)* 38, 534–538.
- Zhang, C.B., Li, Z.B., Yao, C.X., Yin, X.B., Luo, Y.M., Wu, L.H., Song, J., Teng, Y., 2006. Characteristics of spatial variability of soil heavy metal contents in contaminated sites and their implications for source identification. *Soils (in Chinese)* 38, 525–533.
- Zhao, H.K., Gan, J.M., 1998. Study of absorbance of seven elements in atomic absorption spectrometer. *Chinese Journal of Spectroscopy Laboratory (in Chinese)* 15, 104–107.