




Multipotential Toxic Metals Accumulated in Urban Soil and Street Dust from Xining City, NW China: Spatial Occurrences, Sources, and Health Risks

Meng Zhang^{1,2} · Xiaoping Li^{1,2}  · Rui Yang^{1,2} · Jiwen Wang^{1,2} · Yuwei Ai^{1,2} · Yu Gao^{1,2} · Yuchao Zhang^{1,2} · Xu Zhang^{1,2} · Xiangyang Yan^{2,3} · Bin Liu^{1,2} · Hongtao Yu^{2,4}

Received: 21 August 2018 / Accepted: 17 December 2018 / Published online: 10 January 2019
© Springer Science+Business Media, LLC, part of Springer Nature 2019

Abstract

A total of 155 urban soil and 157 dust samples were collected from Xining city (NW, China) with the objective to systematically investigate the spatial occurrences, sources, and health risk status of potential toxic metals (PTMs) bound in urban soil and street dust. Results established by Geographic Information System tools with inverse distance weighted interpolation technique indicated that the spatial status of 24 multi-PTMs varied with their concentration levels in urban soils and street dusts in monitored local areas. However, they had the similar sources in soil and dust. It was found that Bi, Ga, Nb, Ni, Rb, Sr, Th, U, Y, Zr, As, Mn, Nb, Ti, and V would be possibly predominated by nature material, whereas contamination of Ba, Cr, Cu, Pb, and Zn was clearly related to traffic-related sources. Peculiar associations among Sb, Sn, Ce, and Co were possibly enriched in soil and dust very close to the industrial activities. It was noted that PTMs in urban soil was an important contributor to them in dust. Compared with the potential ecological risk index of all PTMs, Sb posed very high risk. The calculated hazard index and cancer risk of all PTMs suggested the acceptable range both to noncarcinogenic and carcinogenic risk to children and adults except for the case of Cr. However, the noncarcinogenic risk for children was usually higher compared with adults. Although the noncarcinogenic and carcinogenic risk were not significant, the risk of Cr above the threshold for children and adults were observed in most local sites, which should be given more attention.

The city is an important symbol of the development and progress of human civilization. It is the main environmental area in which human beings are concentrated in a large

number of living and activities. There is no doubt that urban development has created great wealth for mankind and promoted the development of economy and industry (Zhang et al. 2014). However, it also has caused the deterioration of urban environment, brought a series of environmental pollution problems, and even destroyed the balance of the whole biosphere (Zhao et al. 2014a). Nowadays, more people live in urban areas than in rural areas. Urban soil plays a role of scavenger agent for metal pollutant and adsorptive sink for environmental contamination in nature (Post 1999), which is a relatively young field compared with the traditional soil sciences, which focused primarily on agriculture and forest environments (Horváth et al. 2014). Street dust consists of soil, deposited airborne particulates, construction material, soot, and fume discharged from industry and vehicles—one of the most important host media of environmental pollutants (Post 1999). Urban soil and street dust are strongly influenced by anthropogenic activities, differ greatly from natural soils, and receives a major proportion of potential toxic metals (PTMs) emissions from industrial activities,

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s00244-018-00592-8>) contains supplementary material, which is available to authorized users.

✉ Xiaoping Li
leexpok@163.com

- ¹ Department of Environmental Science, School of Geography and Tourism, Shaanxi Normal University, No. 199 Chang'an South Street, Xi'an 710062, Shaanxi, People's Republic of China
- ² International Joint Research Centre of Shaanxi Province for Pollutant Exposure and Eco-Environmental Health, Xi'an 710062, Shaanxi, People's Republic of China
- ³ School of Chemistry and Chemical Engineering, Shaanxi Normal University, Xi'an 710062, Shaanxi, People's Republic of China
- ⁴ School of Computer, Mathematical and Natural Sciences, Morgan State University, Baltimore, MD 21251, USA

traffic vehicle emissions, municipal waste, as well as commercial and domestic activities (Li and Feng 2012a, b).

Potential toxic metals pollution is a priority environmental pollution in urban environments. Urban soil and dust are the two major emitters of pollutants, which may come from a plethora of sources, such as atmospheric deposition, vehicular traffic, building deterioration, industrial emissions, mining activities, pharmaceuticals, and personal care products (Lin et al. 2017). Pollutants originating from these sources could remain in soil and dust for a long time and can be adverse to human beings even if they have been removed (Li et al. 2017). There are three main characteristics in the process of contaminated soil and dust: long residence term, concealment, and irreversibility. Hence, PTMs are regarded as “chemical time bombs” (Stigliani et al. 1991).

PTM pollution in urban soil and road dust has always been a hotspot for research of environmental science and engineering (Wu et al. 2015). The prolonged presence of pollutants in urban soils and street dust and their close proximity to the human population can significantly amplify the exposure of the urban population to PTMs via inhalation, ingestion, and dermal contact (Dehghani et al. 2017). Although the physical and chemical properties of PTMs are relatively stable, anthropogenic activities could strongly change the process of PTMs in environment and cause a risk to human health.

Numerous studies have revealed the trace metals contamination in urban soils or street dust (Atiemo et al. 2011; Charlesworth et al. 2003; Cheng et al. 2014; Christoforidis and Stamatis 2009; Du et al. 2013; Mihailović et al. 2015; Wei et al. 2015). The scientific literature on trace metals concentrations in urban soil or street dust has focused primarily limited metals, such as Cu, Cr, Ni, Pb, and Zn, and a city-wide systematical investigation was incomplete. Urbanization and industrialization in China have taken place in the past three decades at an unprecedented pace. It has made urban environmental pollution a very important issue (Jaffar et al. 2017). Xining is a valley industrial city in northwestern China, which has experienced rapid urbanization and industrialization, exerting a heavy pressure on its urban environment (Zhao et al. 2014b). A wealth of information on spatial occurrence, sources, and health risk of multi-PTMs associated with rapidly city urbanization and industrialization is lacking. Therefore, the objectives of this study would focus on: (1) investigating the spatial occurrences of these selected 24 PTMs (As, Ba, Bi, Ce, Co, Cr, Cu, Ga, La, Mn, Nb, Ni, Pb, Rb, Sb, Sn, Sr, Th, Ti, U, V, Y, Zn, and Zr) distribution in urban soil and street dust; (2) evaluating the level of contamination in the urban soil and street dust based on pollution indexes; (3) identifying the probable natural or anthropogenic sources of these PTMs; and (4) assessing the potential ecological risk and human health risk to obtain a spatial risk of the pollutants.

Materials and Methods

Study area

Xining (101°45'E, 36°43'N), the capital of Qinghai province of China, lies in the eastern part of Qinghai-Tibet plateau. As an ancient highland city and a major gateway to the Tibetan Plateau on the Yellow River, Xining once had experienced the extensive development many years ago. Nowadays, with the higher speed of urbanization and industrialization, the urban population of Xining has dramatically grown from 941,000 in 2000 to 2,267,000 in 2013, and the Real Gross Domestic Product (GDP) per capita was 5215 Yuan (RMB, name of Chinese currency) in 2000 to 43,346 Yuan in 2013 due to the contributions of industrial business. Xining is not only the capital city of Qinghai province but also has become an important industrial base for mechanical and chemical engineering, fur and milk products, metallurgy, building material manufacture, pharmacy, and electronic industries, etc., in northwest China. Combined with a large number of construction sites, bare soil surfaces, and strong wind in Xining urban city, all create serious pollution in Xining. Compared with western developed countries, the industrial layout in this area obviously lacked well planning, posing a potential risk.

Samples Collection, Preparation, and Analytical Methods

A total of 155 urban soil and 157 street dust samples were collected from asphalt pavements along the main streets and each road branches in the region of Xining (Fig. 1a, b) in September 2014 (dry season). The weather condition was sunny and windless during the sampling period, and no rain had occurred during the 2 weeks before sampling. The sampling sites covered all over the urban area of approximately 350 km², including the traffic, industries, commercial, and residential areas. At each site, road characteristics, land use, and geographic coordinates were recorded. Conforming to the principle of multidensity and random sample collection, each soil sample was collected at 0–20-cm depth from three to five different spots and combined into a composite sample (bulk sample) by the classical cone and quarter technique (Raab et al. 1990), and dust samples were collected by gently sweeping an area of approximately 2–3 m² adjacent to the curb of the impervious surfaces (road, pavement) using plastic utensils (brush and dustpan). All of the soil and dust samples were nearly 200 g and were gathered into clean, self-sealed polyethylene bags, labeled, and transported into the laboratory for subsequent preparation and analysis.

First, all samples were air-dried at an ambient temperature in the laboratory and then sieved by a 2-mm nylon sieve to remove coarse impurities, such as small stones and woody debris. The sieved samples were homogenized into 0.075 mm by electric grinding machine. Next, 4.0 g of each milled soil sample and 2.0 g of boric acid, which would wrap the sample in the bottom and around, were added in the mold synchronously and pressed into a 32-mm-diameter pelleted by using electric tablet machine with 30 t pressure for PTMs concentration detection preparation. The total concentrations of PTMs were directly determined by wavelength dispersive x-ray fluorescence spectrometry (XRF, PANalytical PW2403 apparatus). GSD01-12, GSS01-16, and GBW070041-070046 were selected as analyze standard and quality control samples (Institute of Geophysical and Element Prospecting, Hebei, People's Republic of China) to calibrate and check the accuracy of the XRF. The accuracy test of PTMs in the reference soil samples were given in Table S1 (Supplementary Materials). All of the concentrations were above the limit of detection of each element listed in Table S2 (Supplementary Materials). The relative standard deviation (RSD) of the PTMs were in the range of 5% to 8% (Wu et al. 2015).

Spatial Distribution Analysis

Considerable information might be acquired by portraying the geographic distribution of the elements with Geographic Information System (GIS). GIS maps were plotted to explain the spatial distribution and each potential pollution source of the studied PTMs. Spatial interpolation method was used as the modeling approaches in this study to incorporate information about the geographic position of sample points. The fundamental of spatial interpolation methods was that points closer to each other had more correlations and similarities than those further away (Li et al. 2017; Schloeder et al. 2001). The interpolation technique used in this case was the inverse distance weighted (IDW), which means that the assigned values to unknown points were calculated with a weighted average of the values available at the known points. The software ArcGIS 9.0 (ESRI Inc., CA, USA) was used for mapping and spatial analyzing at present study.

Multivariate Statistical Analysis

Multivariate statistical techniques were extremely useful tools to identify the sources (Li et al. 2017). The relationships among elements were tested using Spearman correlation analysis confirmed by the statistical significance levels at $P < 0.05$ and $P < 0.01$. The Spearman's rank was more appropriate when the data were not normally distributed to correlation analysis. To estimate the relationships in the

elements concentration, to determine potentially influencing environmental factors (Reimann et al. 2002), and to clarify whether the PTMs had similar origins, factor analysis (FA) was regarded as an extension of the correlation analysis to explore hidden multivariate structures in the data (Lazo et al. 2018). Because most environmental data in this study were strongly right-skewed or left-skewed, in this study, the raw data were first log-transformed before using the Windows-based SPSS.19.0 software packages (SPSS Inc., Chicago, IL) to Spearman correlation analysis and factor analysis (FA). All data input and basic statistical analysis, such as maximum, minimum, the arithmetic mean, median, skewness, kurtosis, standard deviation and coefficient of variation of all primary data were computed using Excel 2010.

Contamination Assessment Method

Enrichment factor (EF) of the element was an important index to quantitatively evaluate the degree of pollution and the source of pollution. EF aimed to distinguish and identify metal source originating from anthropogenic and natural means. EF was defined by the following Eq. (1):

$$EF = \frac{(C_x/C_{ref})_{Sample}}{(C_x/C_{ref})_{Background}} \quad (1)$$

where $(C_x/C_{ref})_{Sample}$ was the ratio of PTMs concentration (C_x) to reference metal concentration (C_{ref}) in the sample, and $(C_x/C_{ref})_{Background}$ was the corresponding ratio in the background sample. Elements Fe and Al were most often used with references when calculating the enrichment factor of environmental toxic metal pollutants (Li et al. 2016). In the present study, the background values for PTMs from Xining city soils (A horizon) were used as reference baseline (CNEMC 1990), and Al was selected as the reference element. Degrees of enrichment factor were classified into five categories: $EF < 2$, minimal enrichment; $2 < EF < 5$, moderate enrichment; $5 < EF < 20$, significant enrichment; $20 < EF < 40$, very high enrichment; and $EF > 40$, extremely high enrichment (Li and Feng 2012a; Sutherland 2000).

Potential Ecological Risk Assessment Model

The potential ecological risk was calculated with Eqs. (2) and (3) (Hakanson 1980):

$$C_f^i = \frac{C_i}{C_n^i} \quad (2)$$

$$E_r^i = T_r^i \times C_f^i \quad (3)$$

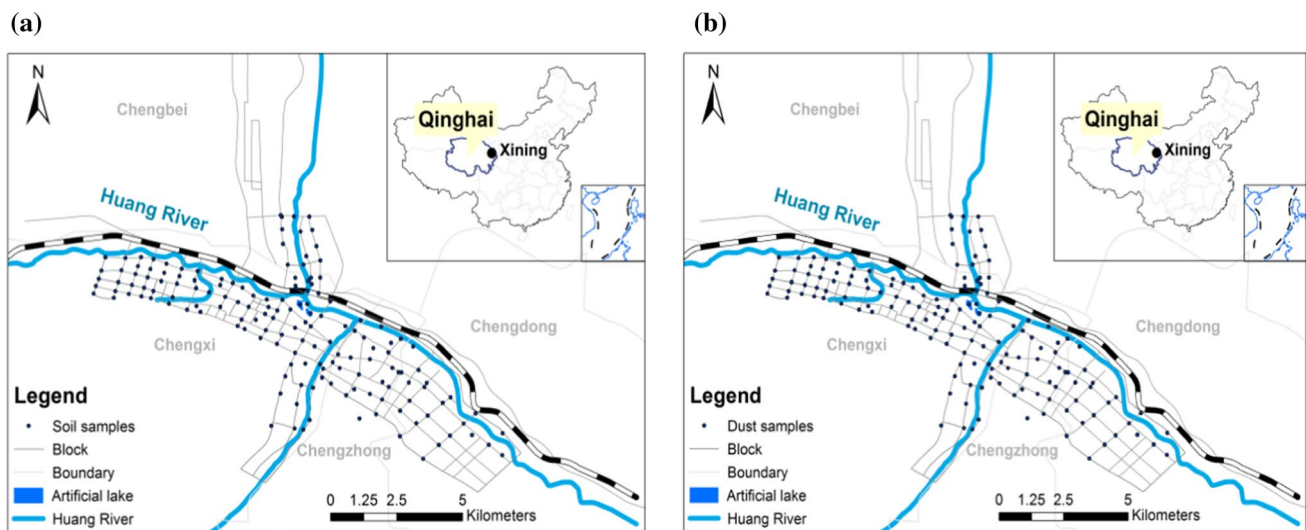


Fig. 1 The location map of the study area (the right upper) and sampling sites of urban soil (a-left) and street dust (b-right) in Xining urban city

C_f^i was the pollution coefficient of a single PTM. C_i was actual content of PTM. C_n^i was the corresponding reference value of i . E_r^i was the potential ecological risk parameter of a single PTM, and T_r^i was the corresponding toxic response factor. The classification of E_r^i was as follows: $E_r^i < 10$ was low risk; $10 < E_r^i < 20$ was moderate risk; $20 < E_r^i < 40$ was considerable risk; $40 < E_r^i < 80$ was very high risk; and $E_r^i > 80$ was extremely high risk. In the study of environmental risk assessment, the background value of Xining soil (CNEMC 1990) was used as the reference value. The standard values C_n of As, Co, Cr, Cu, Mn, Ni, Pb, Sb, Sr, Ti, V, and Zn were 12, 13, 74, 23, 598, 26, 22, 1, 328, 3639, 71, and 60, and the toxic response factor (T_r^i) were 10, 5, 2, 5, 1, 5, 5, 10, 1, 1, 2, and 1, respectively (Xu et al. 2008).

Health Risk Assessment Model

Health risks were classified as noncancer risk and carcinogenic risk. In this study, these PTMs, i.e., As, Ba, Co, Cr, Cu, Ni, Pb, Sb, Sr, Ti, V, and Zn, were selected for health risk assessment. These elements all had chronic noncarcinogenic risks. It was worth emphasizing that As, Co, Cr, Ni, and Pb had cancer risk. On the basis of the movement and transformation of pollutants in the environment, PTMs entered the body mainly through the following three channels: dermal, inhalation, and ingestion.

Exposure Risk Evaluation

The average daily exposure dose received through dermal (ADD_{dermal}), inhalation (ADD_{inh}), and ingestion (ADD_{ing}) routes were calculated using the following Eqs. (4)–(6) adapted from the US-EPA (USEPA 1996,

2001). For carcinogens elements (As, Co, Cr, Ni, and Pb), the lifetime average daily dose (LADD) was calculated in Eq. (7) for the inhalation route in order to assess the cancer risk. Equation (8) was used for calculating the 95% upper confidence limit (UCL) of the arithmetic mean (Gabarron et al. 2017; Li et al. 2013; Lu et al. 2014).

$$ADD_{\text{dermal}} = \frac{C \times SA \times SL \times ABS \times EF \times ED \times CF}{BW \times AT} \quad (4)$$

$$ADD_{\text{inh}} = \frac{C \times \text{Inh}R \times EF \times ED}{PEF \times BW \times AT} \quad (5)$$

$$ADD_{\text{ing}} = \frac{C \times \text{Ing}R \times CF \times EF \times ED}{BW \times AT} \quad (6)$$

$$LADD_{\text{inh}} = \frac{C \times EF}{PEF \times AT} \times \left(\frac{\text{Inh}_{\text{child}} \times ED_{\text{child}}}{BW_{\text{child}}} + \frac{\text{Inh}_{\text{adult}} \times ED_{\text{adult}}}{BW_{\text{adult}}} \right) \quad (7)$$

$$C_{95\% \text{UCL}} = \bar{X} + t_{\alpha, n-1} \cdot \frac{S}{\sqrt{n}} \quad (8)$$

ADD ($\text{mg kg}^{-1} \text{ day}^{-1}$) was the daily dose intake through dermal (ADD_{dermal}), inhalation (ADD_{inh}), and ingestion (ADD_{ing}). ($LADD_{\text{inh}}$) was the lifetime average daily dose intake through inhalation. C (mg kg^{-1}) was the concentration of PTM in the soil or dust. SA ($\text{cm}^2 \text{ day}^{-1}$) was the exposed skin area. SL ($\text{mg cm}^{-2} \text{ day}^{-1}$) was the skin adherence. ABS (dimensionless) was the dermal absorption factor. EF (d a^{-1}) was the exposure frequency. ED (a) was the exposure duration. CF (kg mg^{-1}) was the conversion coefficient. BW (kg) was the standard body weight. AT (day) was the average exposure time. $\text{Inh}R$ ($\text{m}^3 \text{ day}^{-1}$) and $\text{Ing}R$ (mg day^{-1}) were

Table 1 Statistical results of the concentration (mg kg⁻¹) of PTMs in urban soil of Xining City

PTMs	Maximum	Minimum	Mean	Median	Skewness	Kurtosis	Standard deviation	CV (%)	Reference value
As	34.80	3.80	7.65	7.60	8.31	90.60	2.51	0.33	12.00
Ba	479.40	286.20	329.81	325.55	2.77	12.36	25.21	0.08	474.00
Bi	5.90	0.20	2.50	2.40	0.40	0.45	1.10	0.44	0.29
Ce	86.60	49.00	67.59	67.50	-0.02	0.22	6.87	0.10	68.00
Co	30.70	10.30	16.96	15.90	1.20	1.58	3.82	0.23	13.00
Cr	1695.50	98.20	182.54	138.85	7.05	64.77	152.32	0.83	74.00
Cu	96.10	7.10	19.73	18.30	4.87	36.77	8.89	0.45	23.00
Ga	23.80	16.70	20.71	20.90	-0.62	0.37	1.46	0.09	14.00
La	36.20	12.40	24.01	23.65	0.12	0.01	4.09	0.17	35.00
Mn	647.90	286.40	436.96	436.30	0.69	6.52	40.10	0.09	598.00
Nb	19.60	9.20	14.85	14.95	-0.13	-0.91	2.42	0.16	13.00
Ni	37.70	13.00	25.21	25.60	-0.15	0.69	3.89	0.15	26.00
Pb	102.10	13.70	32.57	29.70	2.27	7.88	12.05	0.37	22.00
Rb	108.30	50.00	82.96	84.40	-0.68	0.85	9.73	0.12	92.00
Sb	19.90	0.10	9.33	9.75	-0.34	-0.35	3.76	0.40	1.00
Sn	38.00	1.70	21.90	22.65	-0.46	0.02	6.61	0.30	3.30
Sr	391.90	154.30	242.62	240.25	2.53	0.67	33.43	0.14	328.00
Th	17.60	0.80	12.33	13.10	-1.35	2.47	2.86	0.23	11.00
Ti	2610.00	1580.00	2307.62	2331.00	-1.76	5.41	153.96	0.07	3639.00
U	6.90	0.90	5.02	5.30	-1.34	0.39	1.08	0.22	2.60
V	81.40	46.00	62.95	63.15	-0.30	0.39	5.26	0.08	71.00
Y	34.90	20.00	28.60	29.35	-0.95	0.39	2.69	0.09	23.00
Zn	178.50	21.00	45.13	38.8	2.68	10.75	21.44	0.48	60.00
Zr	277.70	103.80	187.52	188.2	-0.07	0.60	27.85	0.15	219.00

the inhalation and ingestion rate respectively. PEF (m³ kg⁻¹) was the particulate emission factor, which related the concentration of contaminant in soil with the concentration of dust particles in the air. C_{95%UCL} was the 95% upper confidence limit (UCL) of the arithmetic mean. \bar{X} (mg kg⁻¹) was arithmetic mean concentration. a was a parameter associated with confidence coefficient. n was the sample quantity in this study. S was the standard deviation.

Due to the differences in social and cultural environment at home and abroad, the technical parameters needed to be selected through domestic literature research methods, and the recommended values of foreign literature could not be directly quoted (Yu 2011). In this paper, the parameters were modified in the comprehensive consideration of the US-EPA and some related studies in China (Li et al. 2010, 2015; USEPA 1996, 2002). More details are shown in Table S3 in Supplementary Materials.

Risk Characterization

Risk characterization was assessed from the hazard quotient (HQ) (Eq. 9) for each PTM at each site for noncarcinogens and cancer risk (CR) (Eq. 10) for carcinogens.

$$HQ = \frac{ADD}{RfD} \quad (9)$$

$$HI = HQ_{\text{dermal}} + HQ_{\text{inh}} + HQ_{\text{ing}} \quad (10)$$

$$CR = LADD \times CSF \quad (11)$$

ADD (mg kg⁻¹ day⁻¹) was the dermal, inhalation, or ingestion calculated dose from Eqs. (4)–(6). RfD (mg kg⁻¹ day⁻¹) was the corresponding reference dose, which was defined as the intake or dose per unit of body weight. The hazard index (HI) was the sum of the hazard quotient (HQ) from each exposure pathway. HI < 1 means there was no significant risk of noncarcinogenic effect that could be ignored, whereas HI values > 1 suggested that adverse effects might occur (Lu et al. 2014). As an estimate of the upper-limit probability of an individual developing cancer on account of exposure to a particular carcinogen, CR was used to denote cancer risk. CSF (kg day mg⁻¹) was the corresponding carcinogenic slope factor of the lifetime average daily dose (LADD). When CR < 10⁻⁶, it was considered that the risk was negligible. When CR was in the range of 10⁻⁶ to 10⁻⁴, it suggested that there was a certain cancer risk. When CR > 10⁻⁴, it indicated that there was a

Table 2 Statistical results of the concentration (mg kg⁻¹) of PTMs in street dust of Xining City

PTMs	Maximum	Minimum	Mean	Median	Skewness	Kurtosis	Standard deviation	CV (%)	Reference value
As	71.30	0.60	6.00	5.30	10.78	126.62	5.56	0.93	12.00
Ba	1009.10	270.00	344.43	330.30	7.29	71.30	65.09	0.19	474.00
Bi	7.10	0.30	2.86	2.80	0.66	1.96	0.96	0.34	0.29
Ce	99.10	42.30	61.56	60.60	1.09	2.90	8.34	0.14	68.00
Co	66.80	12.50	24.60	23.10	1.83	6.84	7.31	0.30	13.00
Cr	1467.80	88.80	507.77	438.20	1.81	6.95	194.18	0.38	74.00
Cu	112.70	5.80	30.32	26.80	2.41	9.37	14.47	0.48	23.00
Ga	22.80	13.10	18.54	18.50	0.10	1.75	1.47	0.08	14.00
La	31.40	9.30	19.71	19.60	0.08	-0.26	4.16	0.21	35.00
Mn	668.90	243.10	377.69	364.80	2.11	7.21	57.04	0.15	598.00
Nb	24.10	8.20	12.95	12.70	0.82	1.45	2.56	0.20	13.00
Ni	64.50	9.80	23.47	21.30	2.16	6.40	7.95	0.34	26.00
Pb	326.00	20.10	62.82	53.00	3.54	17.23	38.90	0.62	22.00
Rb	88.00	33.80	58.41	57.40	0.54	1.25	8.63	0.15	92.00
Sb	27.50	0.30	8.91	8.90	0.77	1.10	5.23	0.59	1.00
Sn	63.90	2.60	22.81	24.00	0.76	2.33	9.59	0.42	3.30
Sr	900.80	132.80	245.08	240.40	7.65	79.67	62.41	0.25	328.00
Th	22.60	3.60	11.16	11.65	-0.18	2.28	2.61	0.23	11.00
Ti	2528.00	1385.00	1977.87	1951.00	0.43	0.58	189.39	0.10	3639.00
U	6.70	0.70	4.60	4.80	-1.27	2.04	0.98	0.21	2.60
V	72.40	33.10	51.78	51.10	0.98	2.67	5.44	0.11	71.00
Y	33.30	11.10	25.49	25.40	-0.37	1.75	3.15	0.12	23.00
Zn	259.00	27.50	104.84	96.8	1.18	1.84	41.25	0.39	60.00
Zr	359.10	96.7	194.74	190.9	0.62	1.39	39.62	0.20	219.00

significant cancer risk. The reference dose (RfD) and slope factor (SF) of different exposure pathways were shown in Table S4 in Supplementary Materials (Chang and Ye 2014; USEPA 1996, 2002; Zhang et al. 2015).

Results and Discussion

Descriptive Statistics of Raw Dataset in Urban Soil and Street Dust

Urban Soil

Total concentrations and descriptive statistics of soil samples were summarized in Table 1. The background value of Xining soil (CNEMC 1990) was used as the reference value. The arithmetic mean concentrations of Bi, Co, Cr, Ga, Nb, Pb, Sb, Sn, Th, U, and Y were 2.50, 16.96, 182.54, 20.71, 14.85, 32.57, 9.33, 21.90, 12.33, 5.02, and 28.60 mg kg⁻¹ respectively, which were all more than the reference value. The mean concentrations of the PTMs mentioned above to background value ratios decreased as the order of Sb (9.33 times) > Bi (8.62 times) > Sn (6.64 times) > Cr (2.47 times) > U (1.93 times) > Pb (1.480 times) > Ga (1.479 times) > Co (1.30 times) > Y (1.24

times) > Nb (1.14 times) > Th (1.12 times). The average concentrations of As, Ba, Ce, Cu, La, Mn, Ni, Rb, Sr, Ti, V, Zn, and Zr were 7.65, 329.81, 67.59, 19.73, 24.01, 436.96, 5.21, 82.96, 242.62, 2307.62, 62.95, 45.13, and 187.52 mg kg⁻¹, respectively. They did not exceed the background value of Xining soil. The maximum concentrations of Bi, Cr, Cu, Pb, Sb, and Sn were 5.90, 1695.50, 96.10, 102.10, 19.90, and 38.00 mg kg⁻¹, which were 20.34, 22.91, 4.18, 4.64, 19.90, and 11.52 times above the background values. The mean concentrations of Bi, Sb, and Sn were 8.62, 9.33, and 6.64 times the background value respectively, which were significantly higher than the other elements. The standard deviation (SD) and coefficient of variance (CV) indicated that there was wide variation in some PTMs concentrations in soil samples. According to the study by Phil-Eze (2010), if CV ≤ 20% indicated low variability, 21% < CV ≤ 50% was regarded as moderate variability, 51% < CV ≤ 100% indicated high variability, and CV > 100% was considered very high variability. In this study, concentration of Cr showed maximum variability with CV of 83%. As, Bi, Co, Cu, Pb, Sb, Sn, Th, U, and Zn showed moderate variability, while variability of Ti was the lowest. The high CV values of Cr, Zn, Cu, Bi, and Sb reflected their heterogeneity in the soil environment, which further indicated the extensive existence

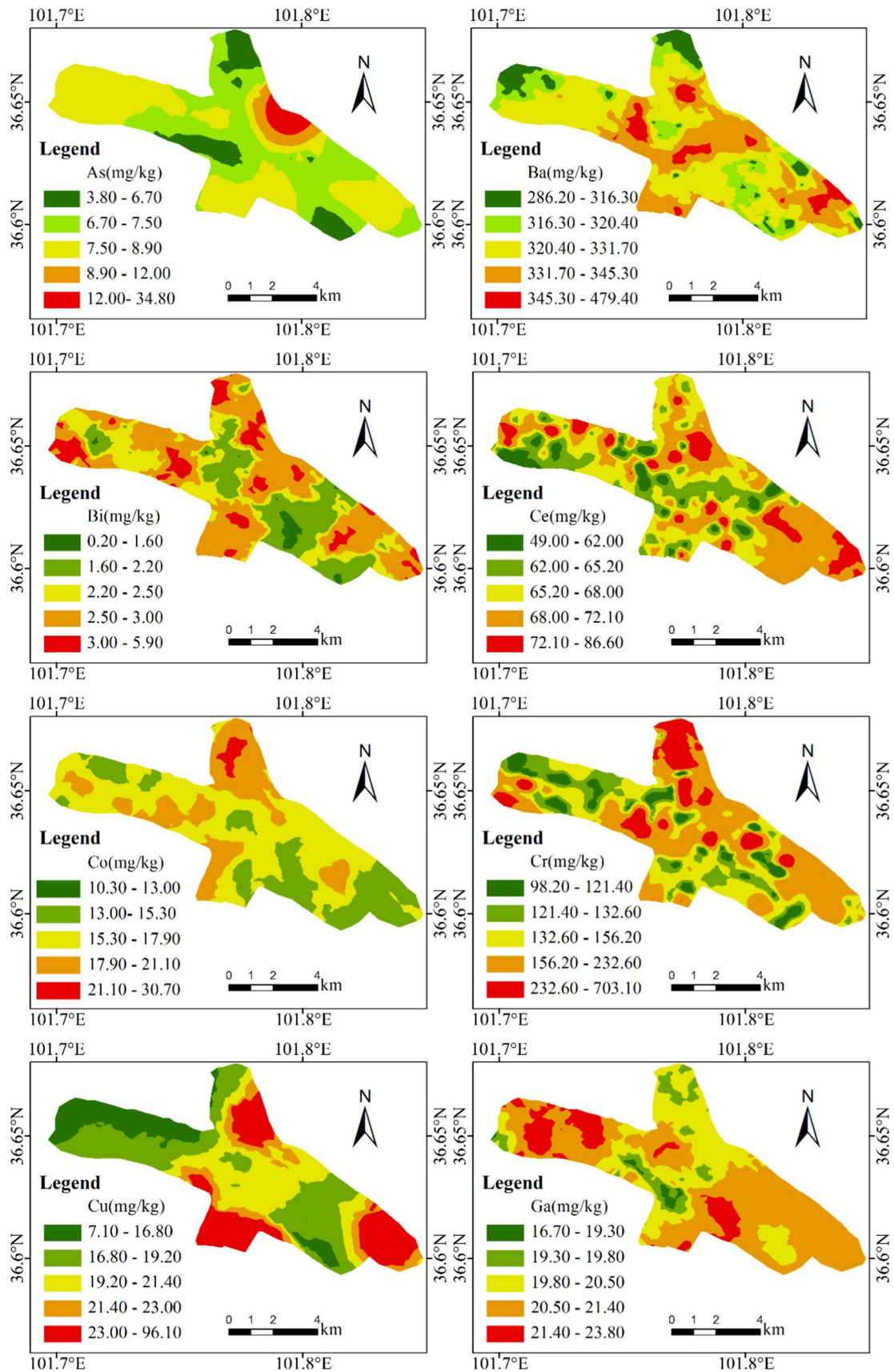


Fig. 2 The regional spatial maps of concentration of PTMs in urban soil of Xining City

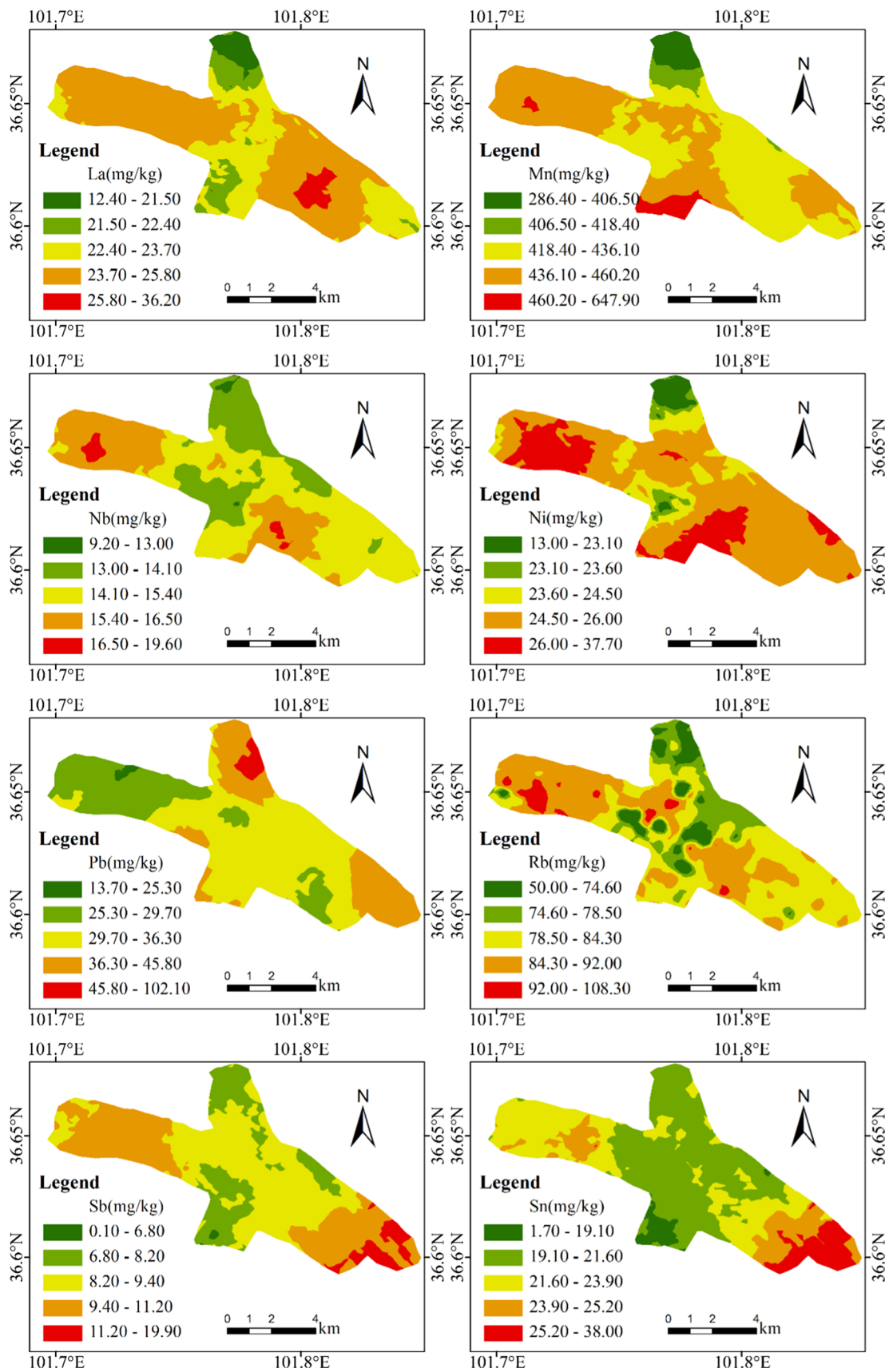


Fig. 2 (continued)

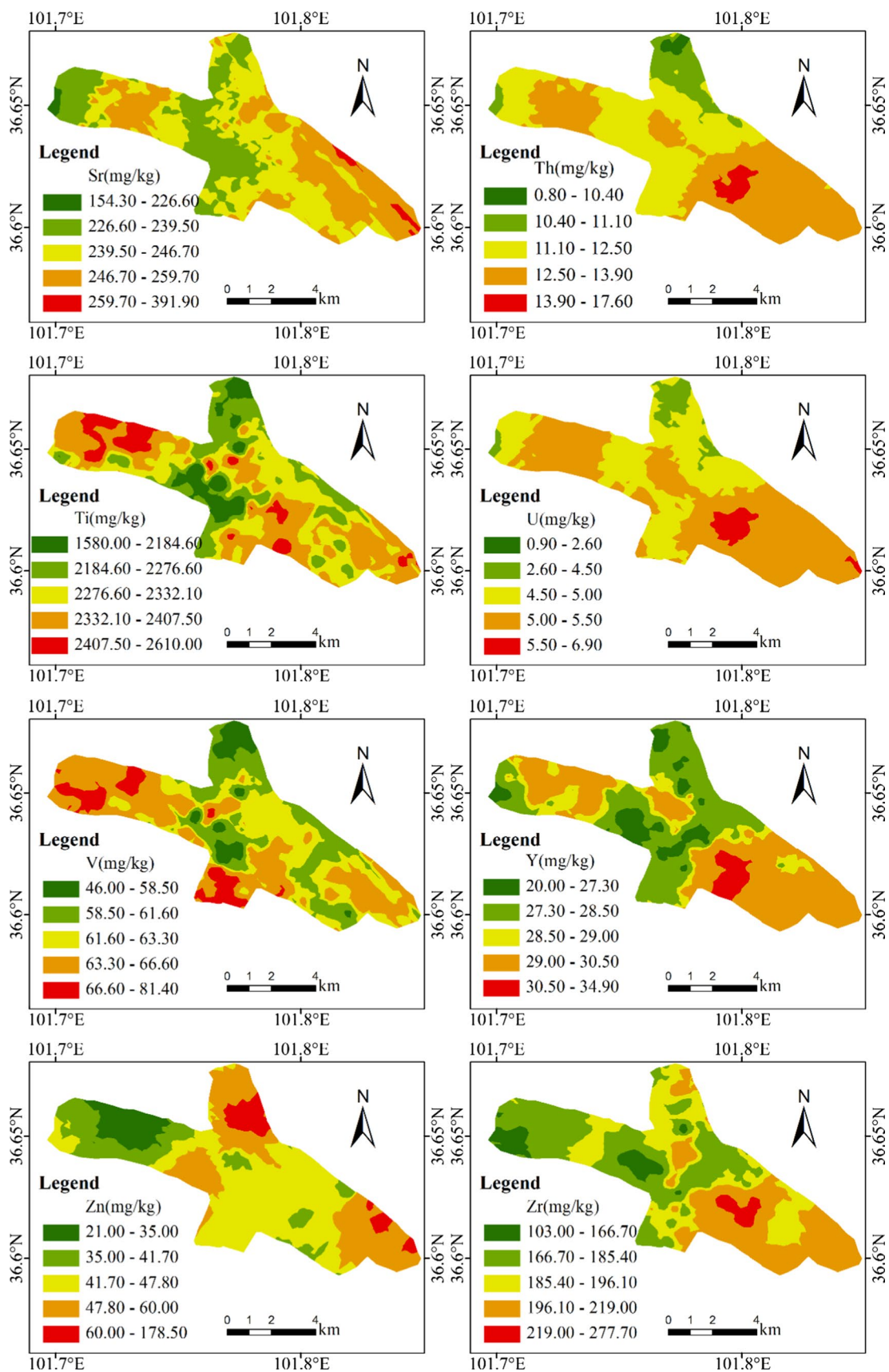


Fig. 2 (continued)

of anthropogenic sources (Han et al. 2006; Karim et al. 2014). The skewness and kurtosis (K–S) test confirmed that the concentrations of these PTMs did not follow a normal distribution, which was normal in geochemical variables. The skewness values of As, Ba, Bi, Co, Cr, Cu, La, Mn, Pb, Sr, and Zn were positive. It manifested that their distribution patterns were right-skewed related to the normal distribution. The skewness of As was maximum, which was 8.31. The rest elements showed minus indicated that their distribution patterns were left-skewed compared with the normal distribution. However, the absolute values of skewness of Bi, Ce, Ga, La, Mn, Nb, Ni, Rb, Sb, Sn, V, Y, and Zr were smaller than others (skewness lower than 1), which confirmed that the concentrations of these elements were normal and close to the normal distribution.

Accordingly, concentrations of some PTMs in soil of Xining City were strongly or slightly affected by human activities, leading accumulation to varying degrees. As, Co, Cr, Cu, Ni, Pb, and Zn contents in Xining soil were compared with those in other cities from different countries (Table S5, Supplementary Materials). As shown in the data of Table S5, the concentrations of Co and Cr were higher than other cities, which might be related to the source of metals emissions, the lifestyle of urban residents, and the level of urban development.

Street Dust

Table 2 showed the total concentrations and descriptive statistics of dust samples. The background value of Xining soil (CNEMC 1990) was used as the reference value as well. The mean concentrations of Bi, Co, Cr, Cu, Ga, Pb, Sb, Sn, Th, U, Y, and Zn exceeded their corresponding background values in Xining soils at 9.86, 1.89, 6.86, 1.32, 1.32, 2.86, 8.91, 6.91, 1.01, 1.77, 1.11, and 1.75 times, respectively. The coefficients of variation ($CV = 100 \text{ SD}/\text{mean}$) were found for As (93%), Bi (34%), Co (30%), Cr (38%), Cu (48%), La (21%), Ni (34%), Pb (62%), Sb (59%), Sn (42%), Sr (25%), Th (23%), U (21%), and Zn (39%), indicating their medium spatial variability, which was probably effected by human activities. The skewness values of Th, U, and Y were negative, which indicated that their distribution patterns were left-skewed related to the normal distribution. The skewness and kurtosis (K–S) test confirmed that the concentrations of Bi, Ce, Ga, La, Nb, Rb, Sb, Sn, Th, Ti, V, Y, Zn, and Zr in soils were normal, whereas other elements were all strongly skewed (skewness higher than 1). The heterogeneous distribution of PTM pollutions from industrial emission might be reflected by the high skewness, kurtosis, and standard deviation values (Li et al. 2017).

Comparison of mean concentrations of the studied metals in dust from Xining with different cities at abroad was summarized in Table S6 (Supplementary Materials). The median value of Cr in the analyzed dusts was much higher

than those reported previously. The difference of Cr contents might be related to the elevated background of soils in the study area (74 mg kg^{-1}), higher than the reported values (Beijing 66.7 mg kg^{-1} , Xi'an 62.5 mg kg^{-1}). Detailed comparisons were clearly presented in Table S6.

Regional Spatial Maps of PTMs in Urban Soil and Street Dust

Urban Soil

The study of the spatial distribution of PTMs in soil and dust was an extremely crucial tool for identifying hot spots with elevated the PTMs concentrations and assessing the potential sources (Pan et al. 2017; Wang et al. 2017). Figure 2 showed the interpolation mappings of spatial spread distribution of As, Ba, Bi, Ce, Co, Cr, Cu, Ga, La, Mn, Nb, Ni, Pb, Rb, Sb, Sn, Sr, Th, Ti, U, V, Y, Zn, and Zr in soil using IDW technique based on ArcGIS10.0 software. The darker red colors show the overlap location of higher PTM concentrations in geochemical maps, whereas the darker green colors indicated both low concentrations and little overlap of areas. The distribution patterns of As, Co, La, Mn, Nb, Pb, Sr, Th, and U indicated low spatial heterogeneity and their abundances vary little in study area. There were some clear heavily polluted hot spots with higher levels mainly located in the northern and western parts of the study area. It was observed that a lot of isolated sites denote hot spots with extremely high values. The concentrations of Cr and Ga in the study area were much higher than the reference values at all locations. One or two hot spots of As, Co, La, Pb, Sb, Sn, Sr, Th, U, Y, and Zr in the spatial distribution maps might be caused by some local point-source of contamination. However, the spatial distributions of Ba, Bi, Ce, Cr, Ga, Ni, Rb, Ti, and V were much more heterogeneous than other metals. It could be observed that several hot spots and strips in maps might result from surface-source of contamination possibly. Distribution pattern in Co, Pb, and Zn, in La, Th, U, Y, and Zr, in Bi, Ce, and Cr, and in Mn, Ti, and V were almost similar.

Street Dust

Spatial maps of As, Ba, Bi, Ce, Co, Cr, Cu, Ga, La, Mn, Nb, Ni, Pb, Rb, Sb, Sn, Sr, Th, Ti, U, V, Y, Zn, and Zr in dust were presented in Fig. 3. It was no exaggeration to say that maps in Fig. 3 were different from those in urban soil (Fig. 2), except for the U, Zn, and Zr. It could be observed as several hot spots and strips in maps of most elements. The high concentrations of dust Ga, La, Rb, and U distribution trend manifested generally similarity in all directions, except the middle region, although their concentrations were diverse, revealing that the origin of these PTMs might be analogous. Dust Cr, Cu, Ni, Pb, and Zn were characterized

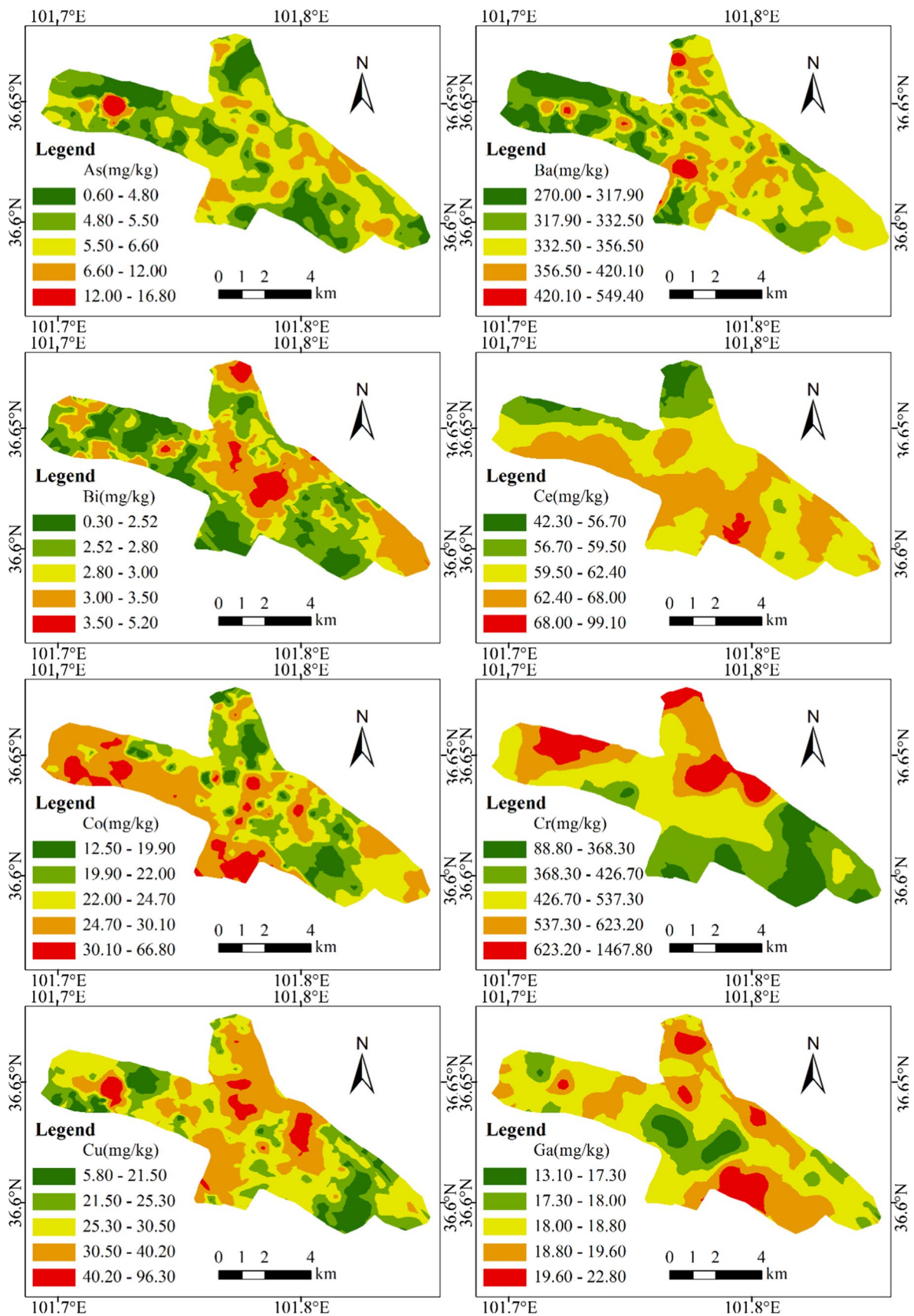


Fig. 3 The regional spatial distributions of concentration of PTMs in street dust of Xining city

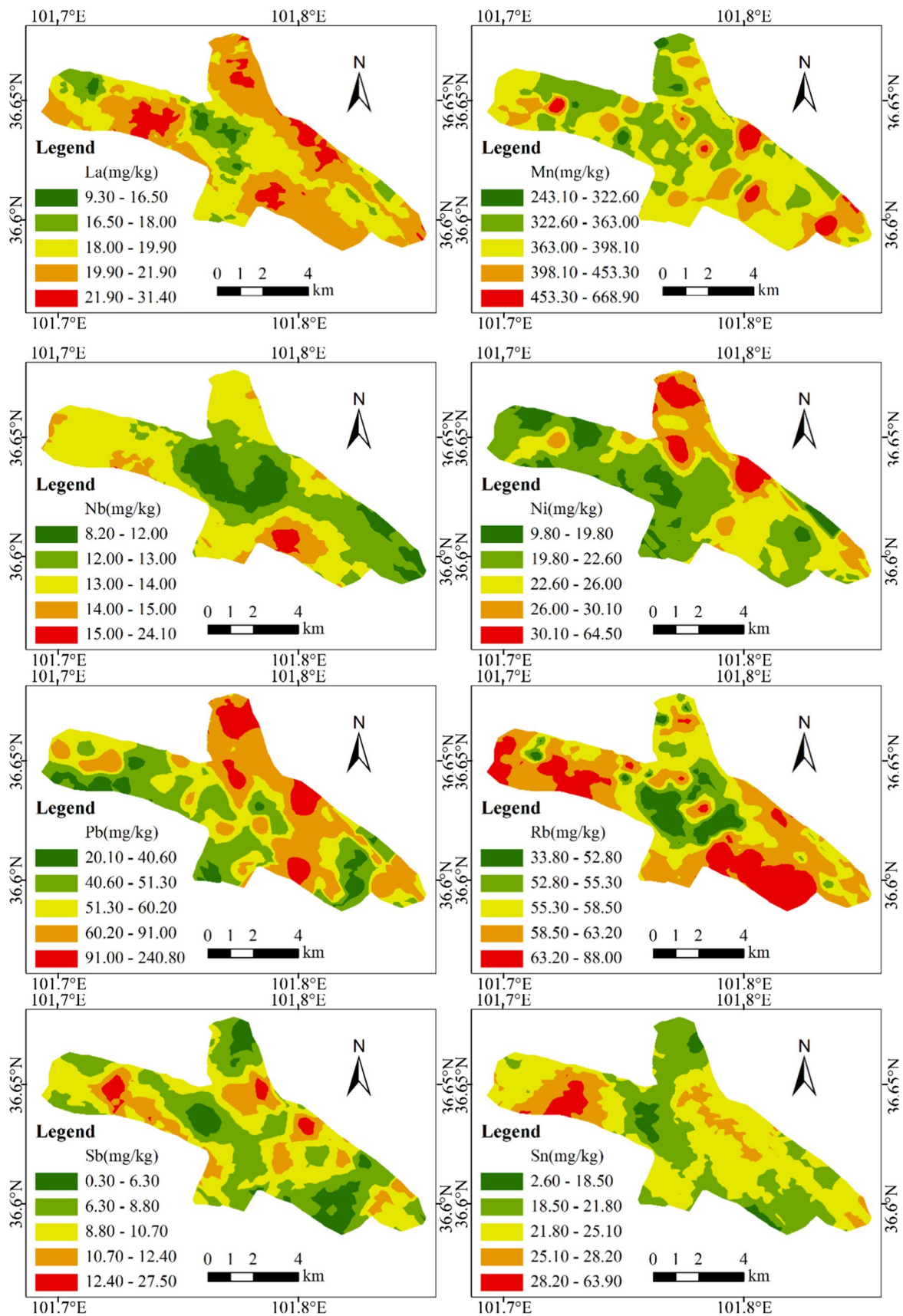


Fig. 3 (continued)

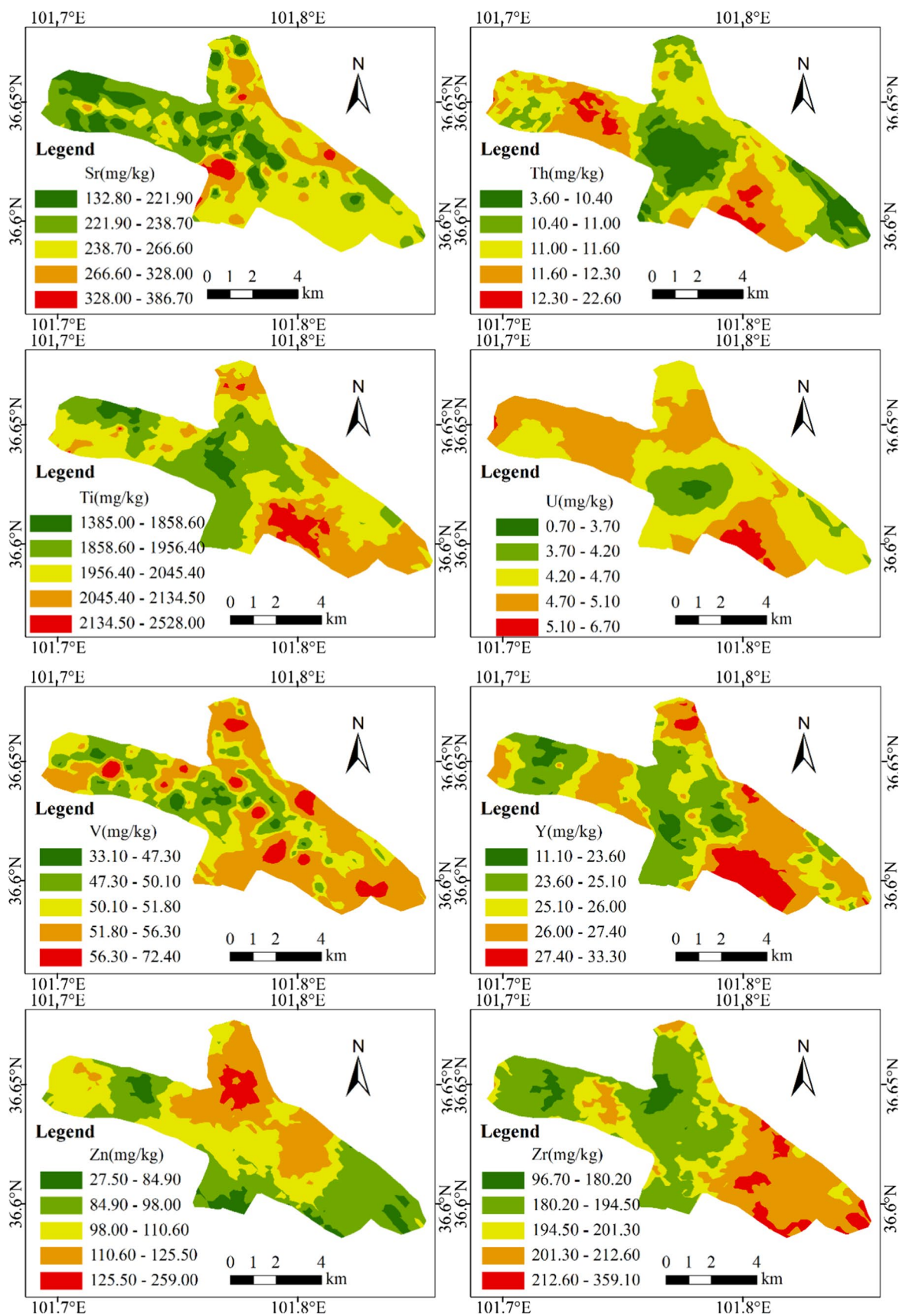


Fig. 3 (continued)

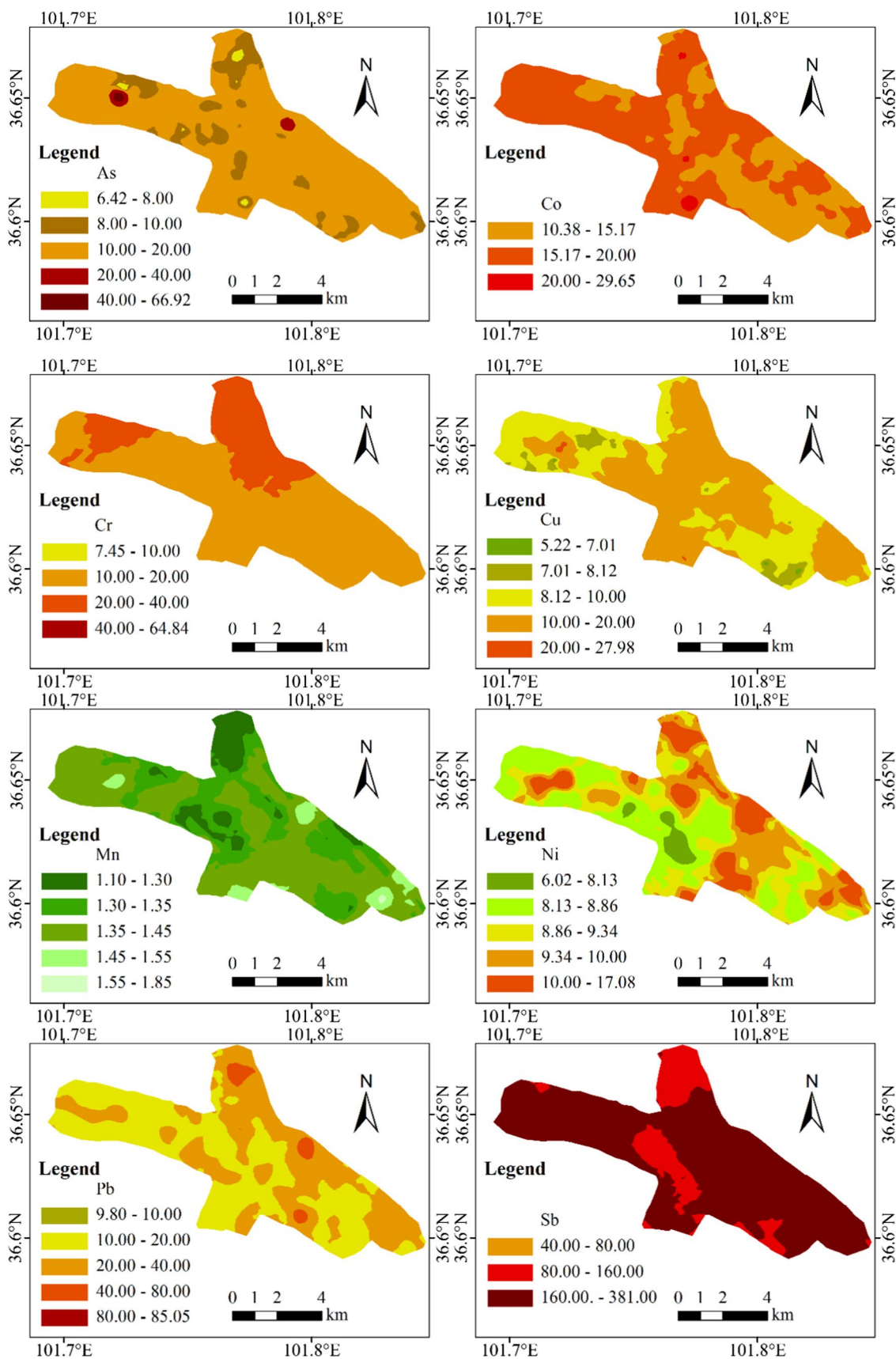


Fig. 4 Spatial distribution of potential ecological risk index of harmful PTMs

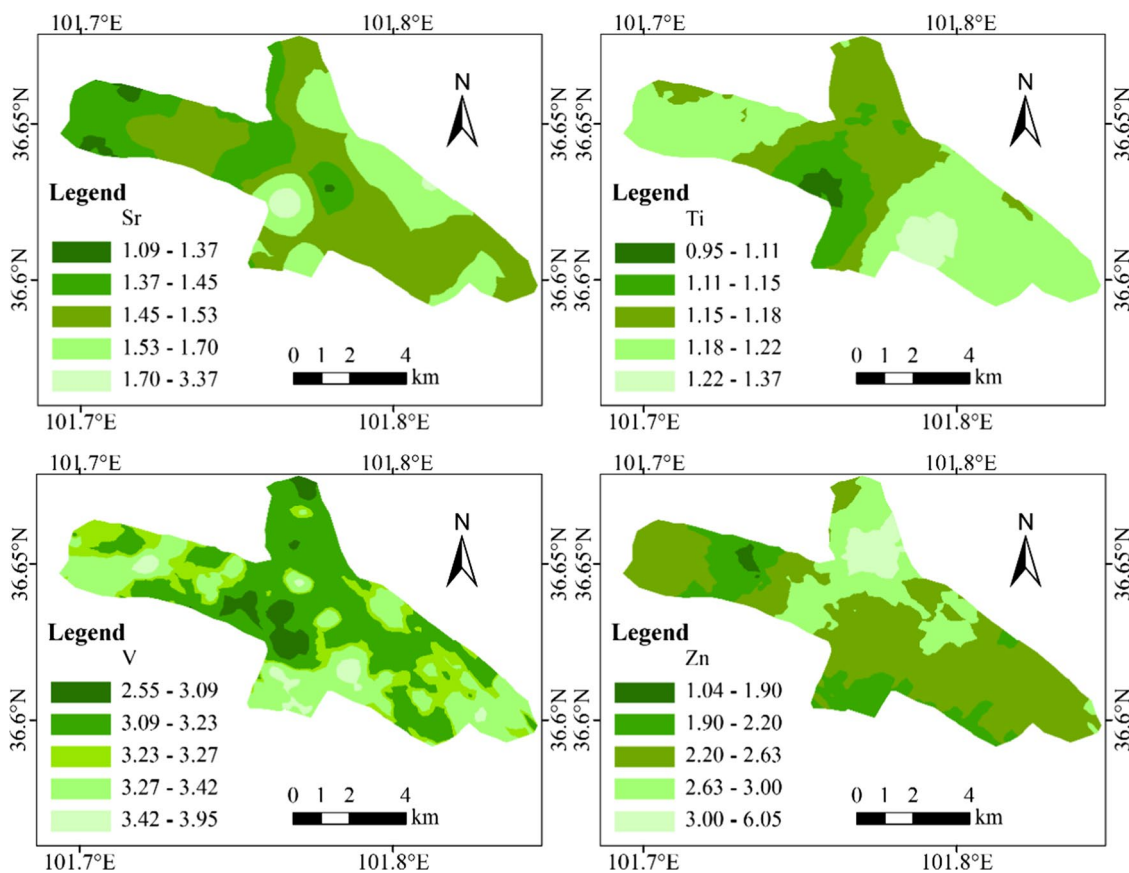


Fig. 4 (continued)

by localized hot-spot patterns in the north of the city. The north region was an important industrial cluster in Xining City, and there were metallurgical, chemical, mechanical manufacturing, and other industrial systems. Accordingly, there was also an important transportation hub for Xining. The geochemical maps indicated that there was likely to be a crucial point-source for these PTMs. The spatial distribution of dust Ce, Mn, Nb, and Sr were dissimilar from the other PTMs, being less variable. Moreover, their concentrations were comparable with the background values, suggesting that these metals might not have been affected by anthropogenic inputs. The Cr distribution in dust displayed a unique pattern, whose trend was more pronounced than other trace metals, showing an increase from southeast to northwest. It should be given more attention because of the possible north industrial agglomeration contribution to the Cr emissions to the environment (Li and Feng 2012b).

Comparison of PTMs Levels in Urban Soil and Street Dust

The level fluxes provided an important tool to understand the relationships of PTMs between in urban soil-street dust and their background. Figure S1 (Supplementary Materials)

highlighted the differences between the PTMs contents in the soils, dust, and from the background based on 10 logarithm. The observations showed that the median of Ti, Mn, Rb, V, Ce, La, Ni, Y, Ga, Nb, As, Th, U, Sb, and Bi in soil were higher than those in dust, and the median of Sr in soil was almost as much as that in dust. The results reflected that the high abundance of those PTMs in the parent local soils were associated with those in street dust. However, other PTMs in the soil were lower than that in dust, which indicated that their PTMs in dust contents were enforced in relation to the anthropogenic activities. The different concentration levels of PTMs in urban soil and street dust suggested that they might have different sources.

Multivariate Analysis and Source Identification of PTMs in Urban Soil and Street Dust

Urban Soil

As a result, the Spearman's correlation coefficients of date from soil samples were listed in Table S7 (Supplementary Materials). The correlation coefficients among these metals could provide some useful information about the sources of these pollutants. The concentration of As showed a

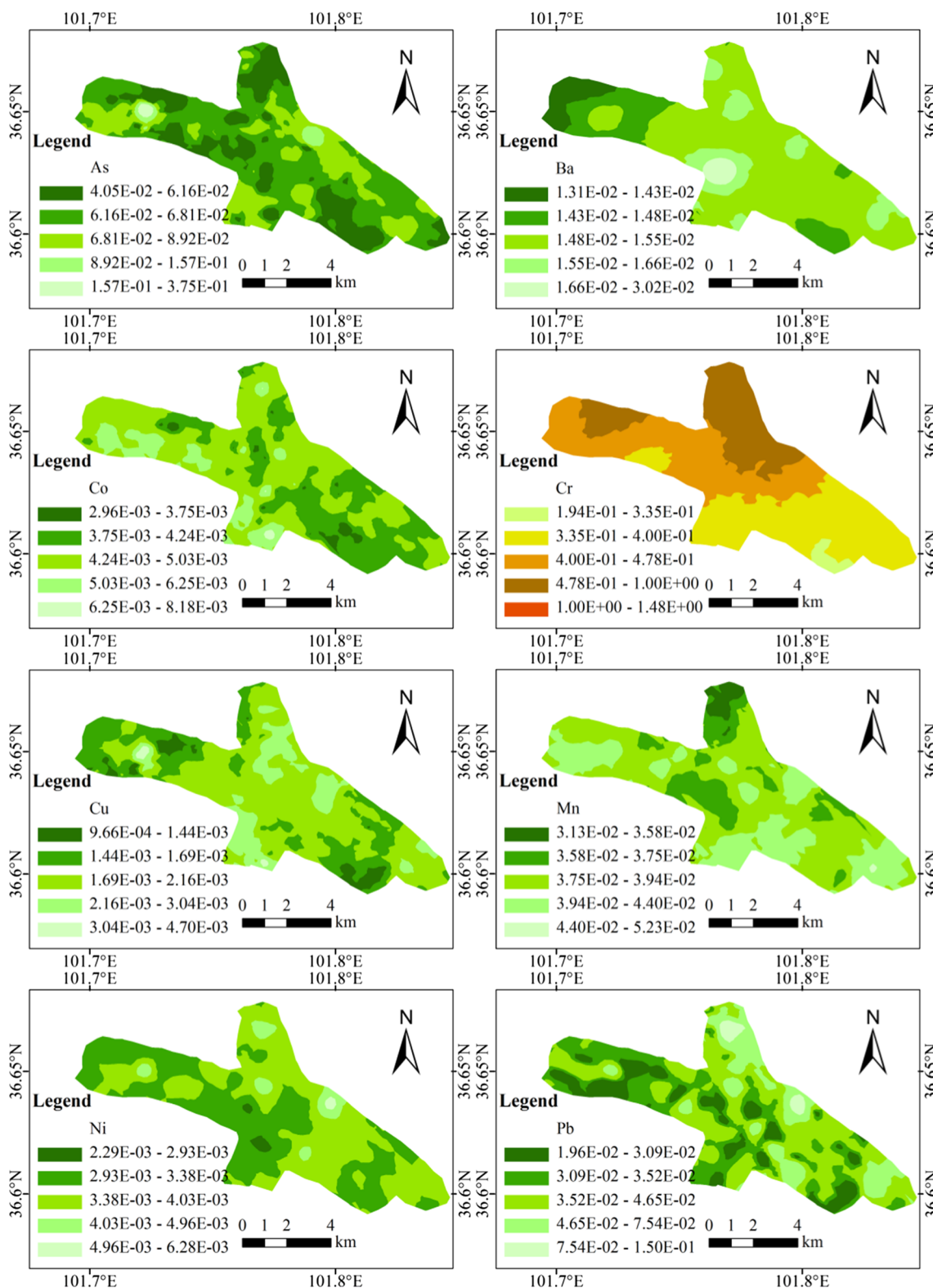


Fig. 5 Spatial distribution of adults' noncarcinogenic risk of harmful PTMs

high significant positive correlation with Mn (0.741), Ni (0.550), Ti (0.503), and V (0.732). Besides, strong correlations were evident for the collocations Mn and Ni (0.597),

Rb (0.559), Ti (0.667), V (0.834); Ni and Rb (0.809), Sb (0.521), Th (0.716), Ti (0.501), U (0.724), V (0.649), Y (0.616), indicating that there was one group of elements,

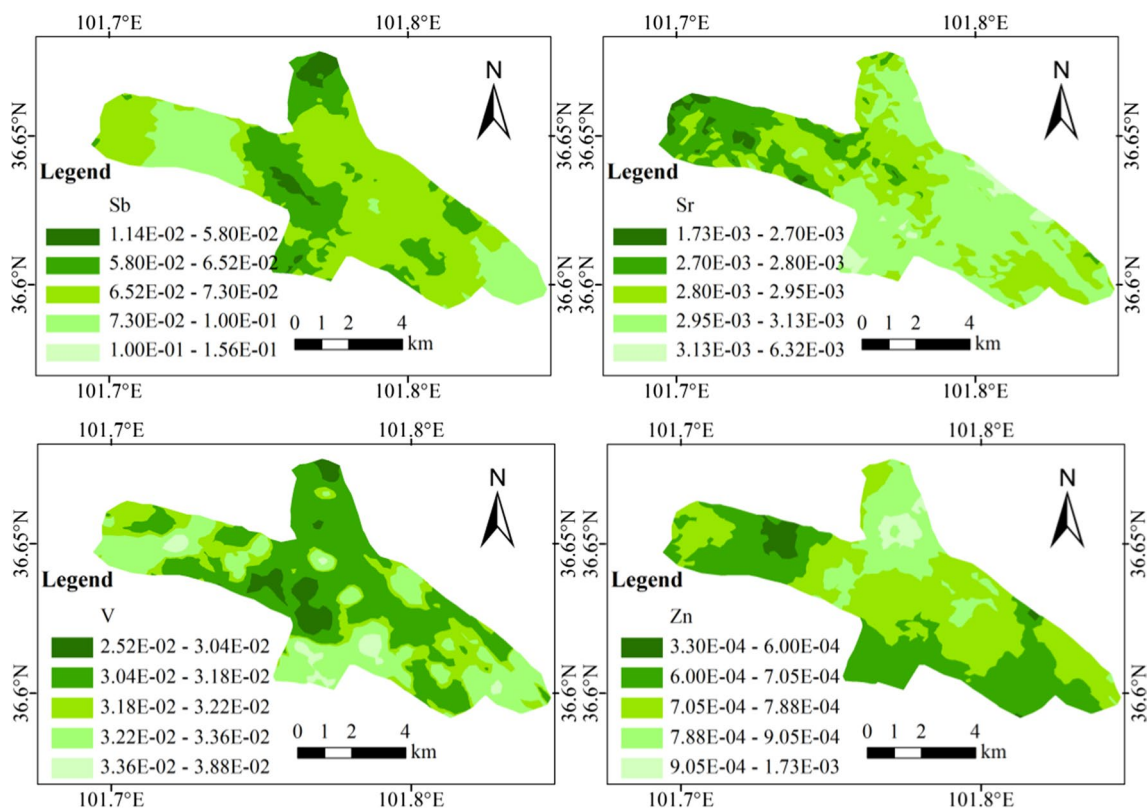


Fig. 5 (continued)

i.e., As–Mn–Ni–Rb–Sb–Th–Ti–U–V–Y, which probably contained similar characteristics and possibly influenced by common factors.

Factor analysis (FA) was performed for the dataset of soil to help to identify the sources of the pollutants. The results of the factor loading matrix were given in Table S8 (Supplementary Materials). As displayed, the first six factors could explain 79.21% of the variance variables, which basically could represent the information contained in the source data, and most of the elements were extracted over 0.6. Elements contain Bi, Ga, Ni, Rb, Sr, Th, U, Y, and Zr were strongly associated with the first factor (PC1), which represented more than 24% of total variance. These metals might have originated from natural materials (Li and Feng 2012b; Shi et al. 2008). The PC2 explained 19.40% of total variance and mainly included As, Mn, Nb, Ti, La, and V. They were usually considered as the representative of the emission elements of firing coal. V also was the main element of petroleum. But in Xining, they were mostly inclined to the natural materials, such as PC1. The third factor (PC3) was dominated by Ba, Cr, Cu, Pb, and Zn, accounting for 16.51% of the total variance, which significantly loaded

on. It was reported that Pb and Zn were related to traffic, because they existed in vehicle exhaust (Men et al. 2018). Cu and Zn also came from the combustion of gasoline and the wear of vehicle during the long-term use. Combined with the spatial distribution of these elements, the content was higher in the north of the city, and the north area was an important traffic hub, which indicated that factor 3 might represent the influence of vehicle transportation activities. The fourth factor (PC4), explaining 8.09% of the total variance, was strongly and positively related to Sb and Sn. The fifth factor (PC5) loaded only on the Ce, indicating 5.73% of the total variance, and Co mainly related with the sixth component (PC6), explaining 4.75% of the total variance. Therefore, the PTMs, Sb, Sn, Ce, and Co, mostly were associated with the industrial activities.

Street Dust

The Spearman's correlation coefficients of As, Ba, Bi, Ce, Co, Cr, Cu, Ga, La, Mn, Nb, Ni, Pb, Rb, Sb, Sn, Sr, Th, Ti, U, V, Y, Zn, and Zr in dust of Xining were listed in Table S9 (Supplementary Materials). Interelement relationships

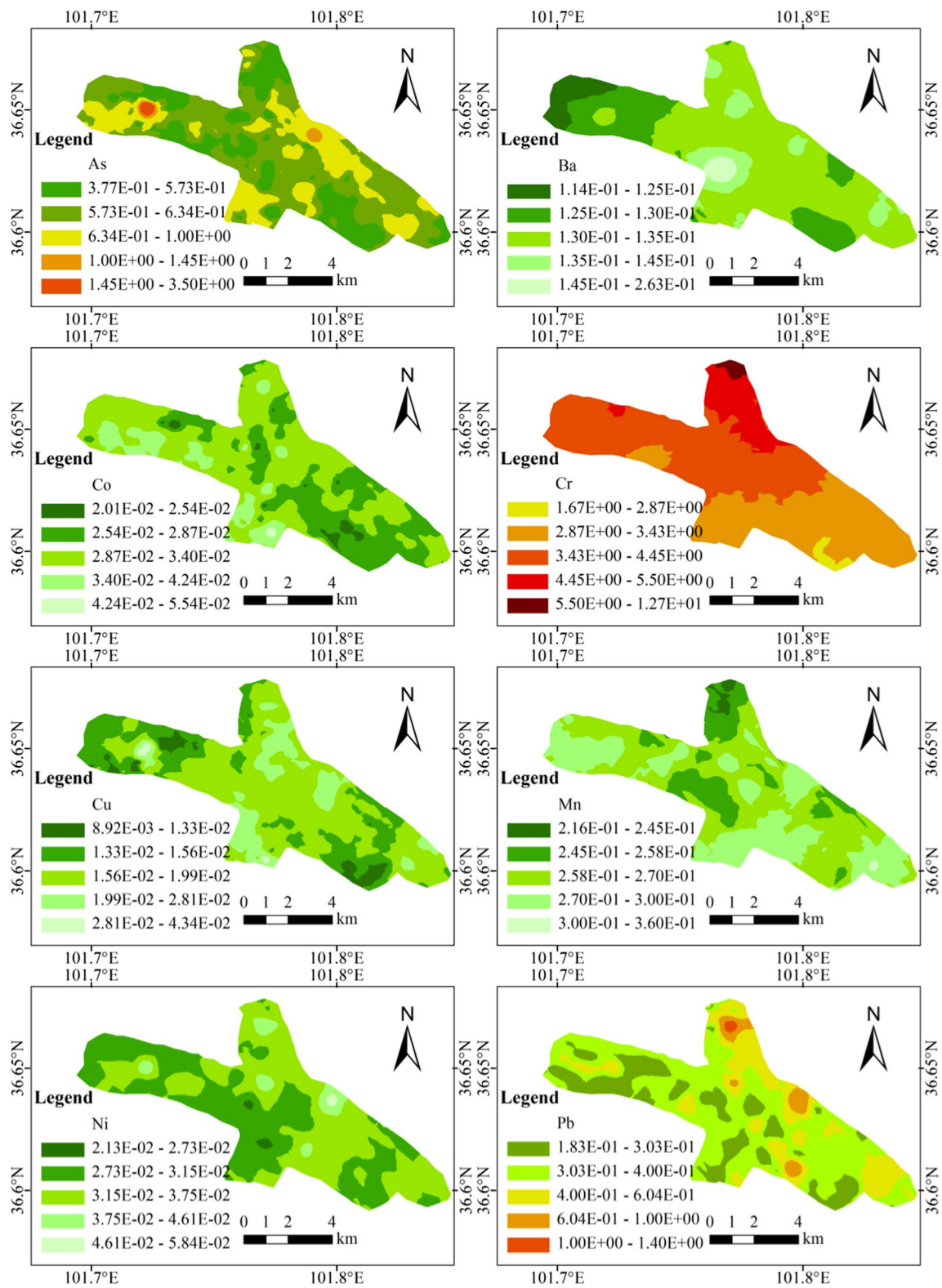


Fig. 6 Spatial distribution of children's noncarcinogenic risk of harmful PTMs

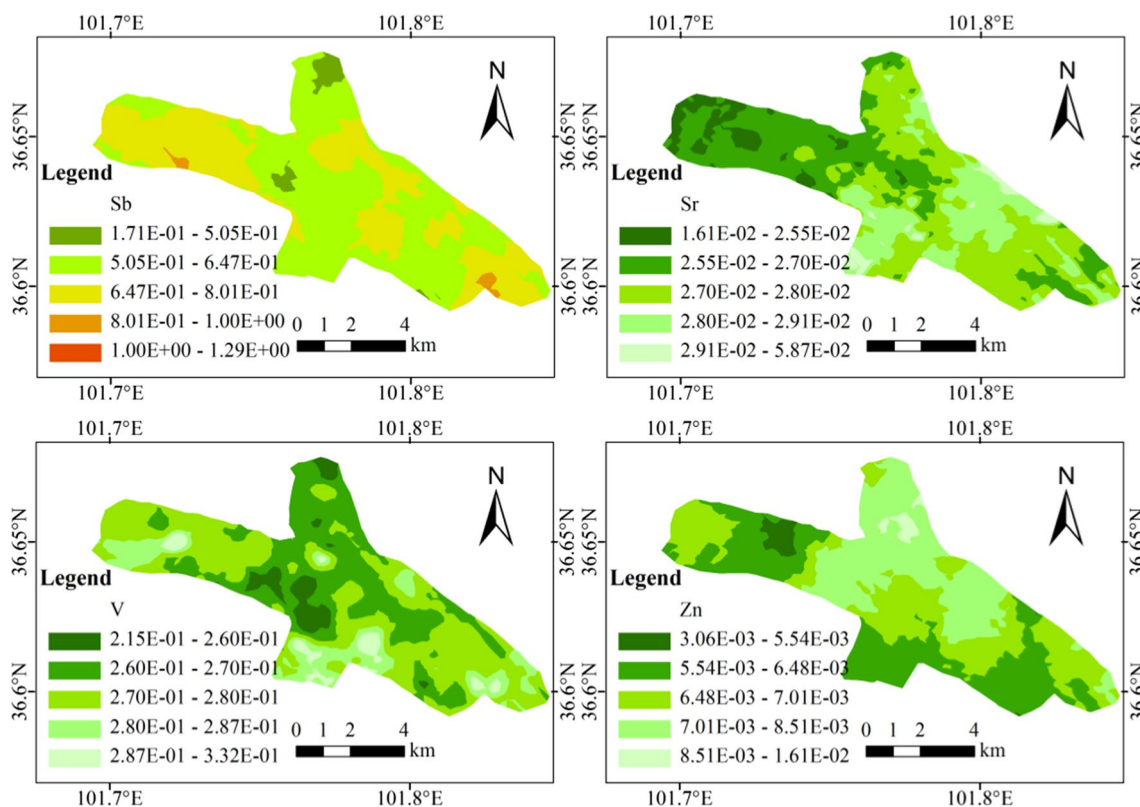


Fig. 6 (continued)

provided interesting information on the sources and pathways of the PTMs. Table S10 (Supplementary Materials) displayed the factor loadings and communalities. The results manifested that six factors were extracted, accounting for 73.38% of the total variance. Factor 1 accounting for 21.03% of the total variance, was loaded primarily by the elements La, Ga, Mn, Nb, Ni, Rb, Ti, and V. Factor 2 was illustrated heavily by Bi, Th, U, Y, and Zr and also moderately by Ga and Rb, which accounted for 17.26% of the total variance and mostly attributed to the natural materials. Factor 3 explained about 13.81% of the variance, which had high loadings on Cr, Cu, Pb, and Zn. Cu was often used in car lubricants, and Cr was widely used to produce stainless steel, automobile parts, aluminum alloy, and titanium alloy (Yang et al. 2011). Hence, Factor 3 could be considered as the traffic emission. Factor 4 was loaded by As, Sb, and Sn and explained 7.86% of the total variance. Factor 5 denoted strongly with Ba, Sr, and moderately with Ce and accounted for 7.53% of the total variance. Factor 6 was dominated by Co, explaining 5.91% of the total variance. Compared with the background values of those metals (As, Sb, Sn, Ba, Sr, Ce, Co), they mainly originated from parent soils contribution and industries possibly.

Although the results of the present study provided preliminary conclusions regarding the origin of each metal,

further studies were necessary to gain a better understanding of their sources.

Enrichment of PTMs in Urban Soil and Street Dust

PTMs enrichment factors calculated with Eq. (1) for each sample in urban soil and street dust were respectively plotted in Figs. S2 and S3 (Supplementary Materials) after removing EF-outliers [extreme outliers marked with circle (○) and mild outliers marked with asterisk (*)]. As shown in EFs boxplots of soil, Bi (EF = 14.88), Sb (EF = 17.22), and Sn (EF = 12.22) had significant enrichment in most soil samples, while Co (EF = 2.17), Cr (EF = 3.31), Ga (EF = 2.66), Ni (EF = 2.02), Pb (EF = 2.34), Th (EF = 2.11), U (EF = 3.68), and Y (EF = 2.22) showed moderate enrichment. The rest PTMs enrichment factors were below 2, meaning that they were minimal enrichment. However, it was obvious that PTMs enrichment factors in dust were not similar to soil. Besides Bi (EF = 21.71), Sb (EF = 20.03), and Sn (EF = 15.96), Cr (EF = 14.80), and Pb (EF = 5.67) in soil also showed significant enrichment compared with soil; their EF values were even higher. Expect dust Cu (EF = 2.68) and Zn (EF = 3.72) have moderate enrichment; the remaining elements showed EFs < 2.

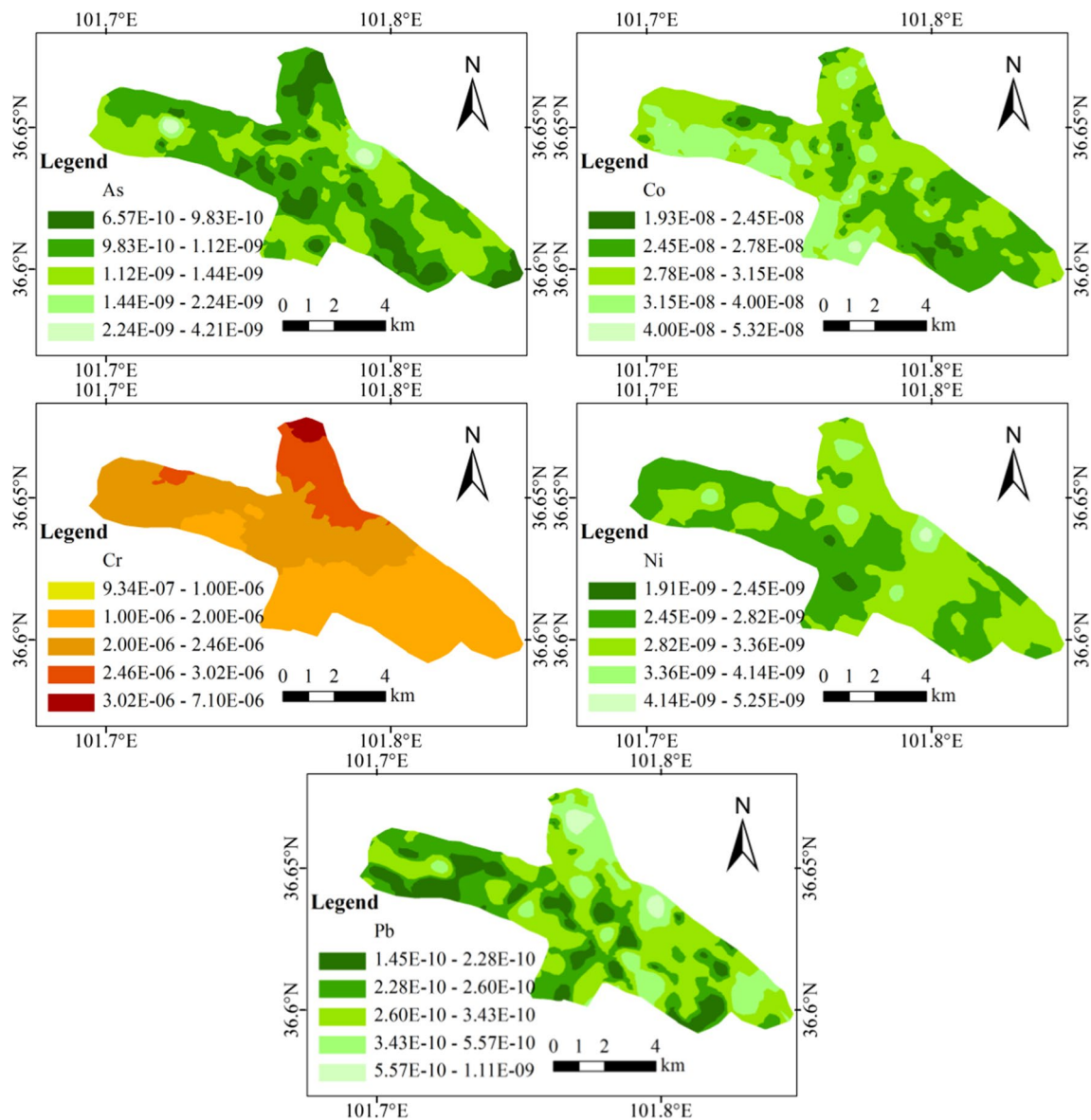


Fig. 7 Spatial distribution of adults' carcinogenic risk of harmful PTMs

Potential Ecological Risk Assessment of PTMs

The spatial distribution of potential ecological risk index (E_r^i) of monomial PTM were shown in Fig. 4. It could be found easily through the change of the color that the severity of pollution of the trace metals decreased as follows: $Sb > Cr > Co > As > Pb > Cu > Ni > V > Zn > Mn \approx Sr \approx Ti$. The most values of E_r^i of Mn, Sr, Ti, V, and Zn were all less than 10, indicating that these trace metals posed minimal ecological risk in the topsoil of the study area. On the contrary, As and Co showed moderate potential ecological risk, because their E_r^i values were in the range

of 10 to 20 at the majority of the study region. Obviously, Cr showed considerable risk at north and northwest, while moderate risk at the rest area. Cu, Ni, and Pb showed different levels in parts of the area; however, the risk trend of these three metals was alike: the E_r^i value was higher in the north and east. For Sb, E_r^i values were > 80 in whole study area, suggesting extremely high potential ecological risk. Sb should be of serious concern because of its potential risks and higher values of adverse effects. Furthermore, chronic Sb exposure might cause reproductive disorders and chromosomal damage (Dehghani et al. 2017).

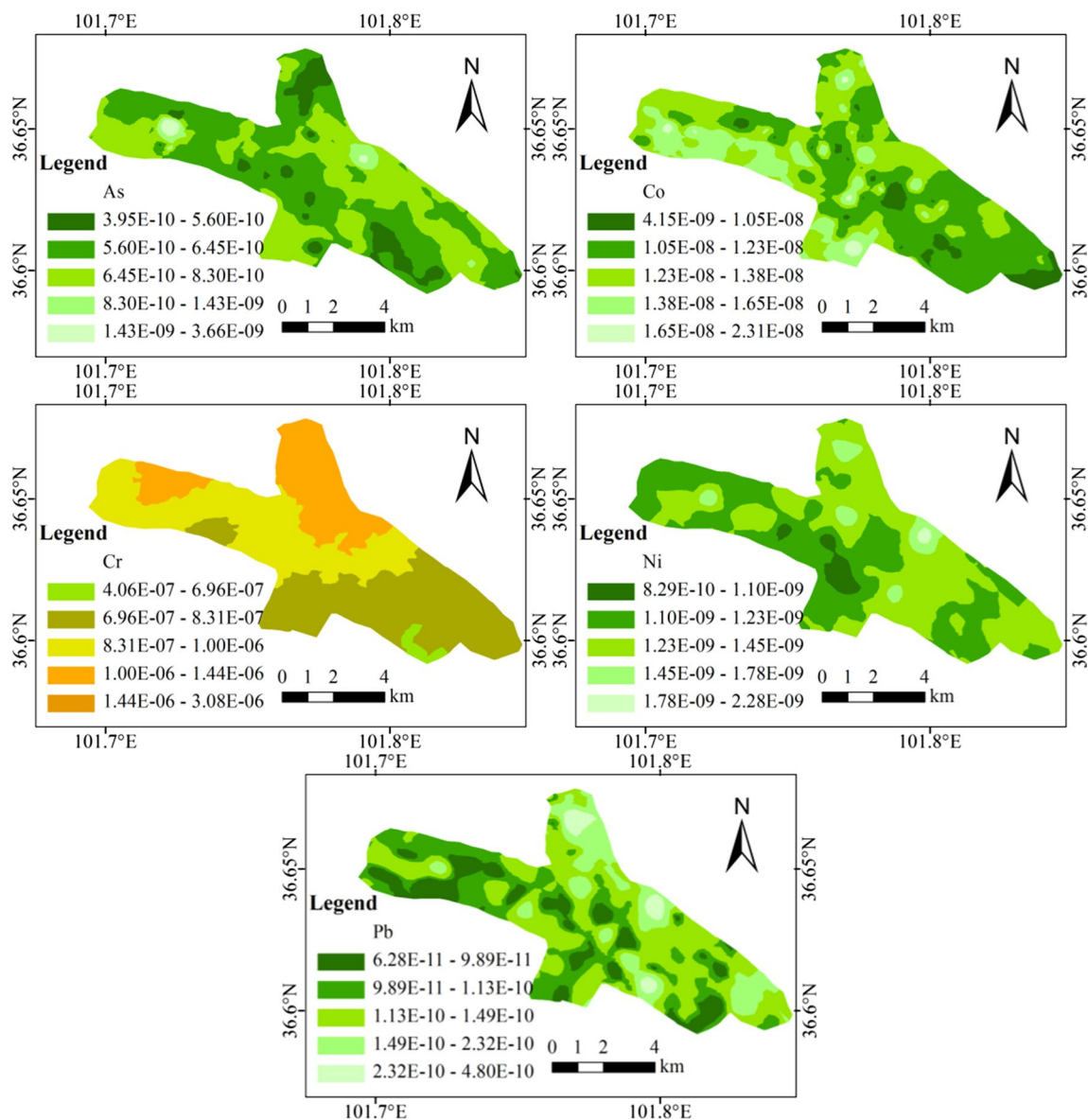


Fig. 8 Spatial distribution of children's carcinogenic risk of harmful PTMs

Health Risk Assessment of PTMs

The diagrams of noncarcinogenic due to harmful PTMs, i.e., As, Ba, Co, Cr, Cu, Mn, Ni, Pb, Sb, Sr, V, and Zn, exposure in urban soil and street dust for both adults and children concerning the population in the studied area were presented in Figs. 5 and 6. Carcinogenic health risks caused by As, Co, Cr, Ni, and Pb exposure for adults and children were shown in Figs. 7 and 8. Generally, the noncarcinogenic health risk for children was usually higher compared with adults. The observed noncarcinogenic risk values (HI) for trace metals were one order of magnitude higher for children than for adults from three routes. Similar results were found in previous studies for urban soil

and dust samples (Dehghani et al. 2017). Except Cr, all the HI values for the elements were lower than the safe level (HI = 1) for adults in the whole study area. However, As and Pb exhibited values close to the safe level at one and two hot spots. For children, HI values of As, Cr, Pb, and Sb were more than the safe value (1) at some sites and close to the safe value at the rest of study area. Lead had extensive toxic effects on the human body, and as the level of blood lead increases, the damage to health would be more serious. Moreover, the central nervous system of children was especially vulnerable to the toxic damage of lead, even low levels of exposure could lead to serious consequences. Pb was a cumulative toxic metal that interferes with the development of the central nervous

system. Therefore, it was particularly toxic to children, causing potentially permanent learning and behavior disorders. Hence, Pb exposure through urban soil and street dust could not be overlooked. Regarding cancer risk, only Cr to both adults and children was harmful, because the calculated CRs were higher than 1×10^{-6} at whole area and north of the city, respectively.

Conclusions

The concentration, spatial distribution, source identification, enrichment factor, potential ecological, and health risk of 24 PTMs (As, Ba, Bi, Ce, Co, Cr, Cu, Ga, La, Mn, Nb, Ni, Pb, Rb, Sb, Sn, Sr, Th, Ti, U, V, Y, Zn, and Zr) in urban soil and street dust from Xining were investigated. The results indicated that multi-PTMs distributions varied in soil and dust; however, they had the similar sources. PTMs Bi, Ga, Nb, Ni, Rb, Sr, Th, U, Y, Zr, As, Mn, Nb, Ti, and V in soils originated with natural materials. Ba, Cr, Cu, Pb, and Zn were related to the traffic emissions. Sb, Sn, Ce, and Co were possibly associated with industrial activities. In addition, parent soil was an important contributor to the PTMs source in dust. It was noted that the PTMs from traffic and industrial emission were strongly enriched and had high potential ecological risk, such as Sb. Although the calculated noncarcinogenic and carcinogenic health risks for humans were in an acceptable range, except for Cr, the calculated noncarcinogenic health risk for children was usually higher compared with adults. Therefore, the higher noncarcinogenic and carcinogenic health risks of Cr in Xining should be given more attention because of its harm to the reproductive health of mankind.

Acknowledgements The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (41471420, 41877517), the project of International Science and Technology Innovation and Cooperation Base (2018GHJD-16), the Natural Science Foundation of Shaanxi Province (2015JM4124), and Fundamental Research Funds for the Central Universities (GK201701010, GK 200902024, and GK201402032).

Author Contributions XL conceived and designed the experiments and organized the manuscript. MZ wrote the manuscript. XL and HY revised the manuscript. RY and JW performed the main experiments and GIS plots. YA, YG, YZ, XZ, XY, and BL contributed the sampling, reagents, materials, and data analysis.

Compliance with Ethical Standards

Conflict of interest This manuscript has been seen by all co-authors, and its submission has been approved by all co-authors. All the authors declare that there is no conflict of interest.

References

- Atiemo MS, Ofori GF, Kuranchie-Mensah H, Tutu AO, Palm NDML, Blankson SA (2011) Contamination assessment of heavy metals in road dust from selected roads in Accra, Ghana. *Res J Environ Earth Sci* 3:473–480
- Chang S, Ye Z (2014) The pollution state and health risk assessment of heavy metals in road dust of Chengdu. *Environ Monit China* 25:790–796
- Charlesworth S, Everett M, McCarthy R, Ordóñez A, de Miguel E (2003) A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK. *Environ Int* 29:563–573. [https://doi.org/10.1016/s0160-4120\(03\)00015-1](https://doi.org/10.1016/s0160-4120(03)00015-1)
- Cheng H, Li M, Zhao C, Li K, Peng M, Qin A, Cheng X (2014) Overview of trace metals in the urban soil of 31 metropolises in China. *J Geochem Explor* 139:31–52. <https://doi.org/10.1016/j.gexplo.2013.08.012>
- Christoforidis A, Stamatis N (2009) Heavy metal contamination in street dust and roadside soil along the major national road in Kavala's region, Greece. *Geoderma* 151:257–263. <https://doi.org/10.1016/j.geoderma.2009.04.016>
- CNEMC (1990) The background values of Chinese soils. Environ Sci Press China, Beijing
- Dehghani S, Moore F, Keshavarzi B, Hale BA (2017) Health risk implications of potentially toxic metals in street dust and surface soil of Tehran, Iran. *Ecotoxicol Environ Saf* 136:92–103. <https://doi.org/10.1016/j.ecoenv.2016.10.037>
- Du Y, Gao B, Zhou H, Ju X, Hao H, Yin S (2013) Health risk assessment of heavy metals in road dusts in urban parks of Beijing, China. *Proc Environ Sci* 18:299–309. <https://doi.org/10.1016/j.proenv.2013.04.039>
- Gabarron M, Faz A, Acosta JA (2017) Soil or dust for health risk assessment studies in urban environment. *Arch Environ Contam Toxicol* 73:442–455. <https://doi.org/10.1007/s00244-017-0413-x>
- Hakanson L (1980) An ecological risk index for aquatic pollution control. a sedimentological approach. *Water Res* 14:975–1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- Han Y, Du P, Cao J, Posmentier ES (2006) Multivariate analysis of heavy metal contamination in urban dusts of Xi'an, Central China. *Sci Total Environ* 355:176–186. <https://doi.org/10.1016/j.scitotenv.2005.02.026>
- Horváth A, Szűcs P, Bidló A (2014) Soil condition and pollution in urban soils: evaluation of the soil quality in a Hungarian town. *J Soils Sedim* 15:1825–1835. <https://doi.org/10.1007/s11368-014-0991-4>
- Jaffar STA, Luo F, Ye R, Younas H, Hu XF, Chen LZ (2017) The extent of heavy metal pollution and their potential health risk in topsoils of the massively urbanized district of Shanghai. *Arch Environ Contam Toxicol* 73:362–376. <https://doi.org/10.1007/s00244-017-0433-6>
- Karim Z, Qureshi BA, Mumtaz M, Qureshi S (2014) Heavy metal content in urban soils as an indicator of anthropogenic and natural influences on landscape of Karachi: a multivariate spatio-temporal analysis. *Ecol Indic* 42:20–31. <https://doi.org/10.1016/j.ecoli.2013.07.020>
- Lazo P, Steinnes E, Qarri F et al (2018) Origin and spatial distribution of metals in moss samples in Albania: a hotspot of heavy metal contamination in Europe. *Chemosphere* 190:337–349. <https://doi.org/10.1016/j.chemosphere.2017.09.132>
- Li X, Feng L (2012a) Geostatistical analyses and fractionation of heavy metals in urban soil from industrial district in Weinan, NW China. *Environ Earth Sci* 67:2129–2140. <https://doi.org/10.1007/s12665-012-1653-8>

- Li X, Feng L (2012b) Multivariate and geostatistical analyzes of metals in urban soil of Weinan industrial areas, Northwest of China. *Atmos Environ* 47:58–65
- Li F, Hu C, Zhang Y, Shen M, Yang X (2010) Environmental impact and health risk assessment of heavy metals in street dust in Shenyang, Liaoning province. *J Meteorol Environ* 26:59–64
- Li H, Qian X, Hu W, Wang Y, Gao H (2013) Chemical speciation and human health risk of trace metals in urban street dusts from a metropolitan city, Nanjing, SE China. *Sci Total Environ* 456–457:212–221. <https://doi.org/10.1016/j.scitotenv.2013.03.094>
- Li X, Xu C, Liu X, Liu J, Zhang X (2015) Bioactivity and environment risk of heavy metals in urban soil from Baoji City, P.R. China. *Acta Sci Circumst* 35:1241–1249
- Li F, Zhang J, Huang J, Huang D, Yang J, Song Y, Zeng G (2016) Heavy metals in road dust from Xiandao District, Changsha City, China: characteristics, health risk assessment, and integrated source identification. *Environ Sci Pollut Res* 23:13100–13113. <https://doi.org/10.1007/s11356-016-6458-y>
- Li X, Wu T, Bao H et al (2017) Potential toxic trace element (PTE) contamination in Baoji urban soil (NW China): spatial distribution, mobility behavior, and health risk. *Environ Sci Pollut Res* 24:19749–19766. <https://doi.org/10.1007/s11356-017-9526-z>
- Lin M, Gui H, Wang Y, Peng W (2017) Pollution characteristics, source apportionment, and health risk of heavy metals in street dust of Suzhou, China. *Environ Sci Pollut Res* 24:1987–1998. <https://doi.org/10.1007/s11356-016-7934-0>
- Lu X, Wu X, Wang Y, Chen H, Gao P, Fu Y (2014) Risk assessment of toxic metals in street dust from a medium-sized industrial city of China. *Ecotoxicol Environ Saf* 106:154–163. <https://doi.org/10.1016/j.ecoenv.2014.04.022>
- Men C, Liu R, Xu F, Wang Q, Guo L, Shen Z (2018) Pollution characteristics, risk assessment, and source apportionment of heavy metals in road dust in Beijing, China. *Sci Total Environ* 612:138–147. <https://doi.org/10.1016/j.scitotenv.2017.08.123>
- Mihailović A, Budinski-Petković L, Popov S, Ninkov J, Vasin J, Ralević NM, Vučinić Vasić M (2015) Spatial distribution of metals in urban soil of Novi Sad, Serbia: GIS based approach. *J Geochem Explor* 150:104–114. <https://doi.org/10.1016/j.gexplo.2014.12.017>
- Pan H, Lu X, Lei K (2017) A comprehensive analysis of heavy metals in urban road dust of Xi'an, China: contamination, source apportionment and spatial distribution. *Sci Total Environ* 609:1361–1369. <https://doi.org/10.1016/j.scitotenv.2017.08.004>
- Phil-Eze PO (2010) Variability of soil properties related to vegetation cover in a tropical rainforest landscape. *J Geogr Reg Plan* 3:177–184
- Post JE (1999) Manganese oxide minerals: crystal structures and economic and environmental significance. *Proc Natl Acad Sci* 96:3447–3454. <https://doi.org/10.1073/pnas.96.7.3447>
- Raab GA, Bartling MH, Stapanian MA, Cole WH, Tidwell RL, Cappo KA (1990) The homogenization of environmental soil samples in bulk. In: Simmons MS (ed) *Hazardous waste measurements*. Lewis Publishers, Chelsea
- Reimann C, Filzmoser P, Garrett RG (2002) Factor analysis applied to regional geochemical data: problems and possibilities. *Appl Geochem* 17:185–206
- Schloeder CA, Zimmerman NE, Jacobs MJ (2001) Comparison of methods for interpolating soil properties using limited data. *Soil Sci Soc Am J* 65:470–479. <https://doi.org/10.2136/sssaj2001.652470x>
- Shi G, Chen Z, Xu S, Zhang J, Wang L, Bi C, Teng J (2008) Potentially toxic metal contamination of urban soils and roadside dust in Shanghai, China. *Environ Pollut* 156:251–260. <https://doi.org/10.1016/j.envpol.2008.02.027>
- Stigliani WM, Doelman P, Salomons W, Schulin R, Smidt GRB, Van der Zee SEATM (1991) Chemical time bombs: predicting the unpredictable. *Environ Sci Policy Sustain Dev* 33:4–30. <https://doi.org/10.1080/00139157.1991.9931383>
- Sutherland RA (2000) Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. *Environ Geol* 39:611–627
- USEPA (1996) *Soil screening guidance: technical background document*. Environmental Protection Agency, Washington
- USEPA (2001) *Supplemental guidance for developing soil screening levels for superfund sites*. Environmental Protection Agency, Washington
- USEPA (2002) *Supplemental guidance for developing soil screening levels for super found sites*. Office of Soil Waste and Emergency Response, Washington
- Wang G, Zhang S, Xiao L et al (2017) Heavy metals in soils from a typical industrial area in Sichuan, China: spatial distribution, source identification, and ecological risk assessment. *Environ Sci Pollut Res* 24:16618–16630. <https://doi.org/10.1007/s11356-017-9288-7>
- Wei X, Gao B, Wang P, Zhou H, Lu J (2015) Pollution characteristics and health risk assessment of heavy metals in street dusts from different functional areas in Beijing, China. *Ecotoxicol Environ Saf* 112:186–192. <https://doi.org/10.1016/j.ecoenv.2014.11.005>
- Wu S, Peng S, Zhang X et al (2015) Levels and health risk assessments of heavy metals in urban soils in Dongguan, China. *J Geochem Explor* 148:71–78. <https://doi.org/10.1016/j.gexplo.2014.08.009>
- Xu Z, Ni S, Tuo X, Zhang C (2008) Calculation of heavy metals' toxicity coefficient in the evaluation of potential ecological risk index. *Environ Sci Technol* 31:112–115
- Yang Z, Lu W, Long Y, Bao X, Yang Q (2011) Assessment of heavy metals contamination in urban topsoil from Changchun City, China. *J Geochem Explor* 108:27–38. <https://doi.org/10.1016/j.gexplo.2010.09.006>
- Yu Y (2011) *Ealth risk assessment and management techniques of environmental pollution*. China Environmental Science Press, Beijing
- Zhang M, Lu X, Chen H, Gao P, Fu Y (2014) Multi-element characterization and source identification of trace metal in road dust from an industrial city in semi-humid area of Northwest China. *J Radioanal Nucl Chem* 303:637–646. <https://doi.org/10.1007/s10967-014-3300-1>
- Zhang C, Li Y, Wu M, Dai Z, Han D (2015) Heavy metals contamination and health risk assessment of urban soil in old industrial area. *Ind Saf Environ Protect* 41:25–29
- Zhao N, Lu X, Chao S (2014a) Level and contamination assessment of environmentally sensitive elements in smaller than 100 μm street dust particles from Xining, China. *Int J Environ Res Public Health* 11:2536–2549. <https://doi.org/10.3390/ijerph110302536>
- Zhao N, Lu X, Chao S, Xu X (2014b) Multivariate statistical analysis of heavy metals in less than 100 μm particles of street dust from Xining, China. *Environ Earth Sci* 73:2319–2327. <https://doi.org/10.1007/s12665-014-3578-x>