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Trace metals in soil, dust, and tree leaves of the urban environment, Guangzhou, China

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Metals have been constantly introduced to urban environments via various point and non-point sources of pollution, and have contaminated different urban compartments (sample types). However, most research projects have focused on a single environmental compartment to characterize urban metal contamination. In the present study, an integrated sampling program that includes surface soils, different size fractions of soil and road dust (<50 μm, 50–100 μm, 100–250 μm, and 250–1000 μm), tree leaves, and grasses, was conducted in a typical urban area of Guangzhou, China. The aim of the study was to investigate the interrelationships among the metal pollutants in these samples. The concentrations of trace metals varied greatly among different sample types, and their distribution was generally in the following order: road dust > soil dust $\geqslant$ surface soils $\approx$ top soils > grasses $\geqslant$ tree leaves. As for the relationships among the trace metals, different combinations were seen among the sample types, indicating different loadings of trace metals in the sampling medium. Significant correlations of metal concentrations were found between tree leaves and the smallest (<50 μm) fraction of road dust, and between soil dust (50–100 μm) and surface soils, suggesting that trace metals in these samples may influence each other.

urban environment, trace metals, soil, dust, tree leaf, grass

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Increasingly, urban environments, especially those in developing countries, are being degraded due to intensified anthropogenic activities, posing a potential health threat to more than half of the global population, who live in urban areas. Trace metal contamination is an important factor in this degradation. Ajmone-Marsan and Biasioli [1] reviewed current literature on trace metal pollution in the urban soils of about 94 world cities. Their results revealed that most cities are contaminated by one or more types of metals. Similarly, Luo et al. [2] examined trace metal contamination in urban soils from 21 cities of China, and found that the mean or median concentrations of trace metals in urban soils were significantly higher than the corresponding background soil values. Furthermore, trace metal concentrations were usually high in old industrial cities, where metals had been deposited from the emissions of vehicles, power plants, and industrial processes [2].

Soil and dust are important sinks of trace metal contaminants in urban environments. Toxic metals loaded in dust and loose parts of surface soil may have adverse effects on the health of humans, especially children, from the involuntary or direct ingestion of soil particles via the "hand to mouth" pathway. For example, many studies have pointed to a significant correlation between the blood lead levels (BLLs) of children and Pb concentration in urban soil/dust [3–5]. Furthermore, re-suspended soil or road dust is likely to contribute significantly to fine particulate matter (<10 μm, PM_{10}) in air, a topic that has been widely studied in relation with the respiratory health of humans [6–8]. Therefore, the trace metals present in soil/dust might have a considerable influence on the composition of PM_{10} in the surrounding air environment [9]. The potential adverse health effects of

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trace metals may be different between road dust and urban soils due to the different metal loadings and chemical forms associated with them. In addition, road dust and urban soils can influence each other in close urban settings. However, many previous studies have focused on either road dust or urban soil alone, and have not fully investigated the relationship between the two or the influence of metal loadings. Similarly, the differences in trace metal concentrations between the loose parts of soil (soil dust) and among different layers of soil (e.g., 0–3 or 0–15 cm) in an urban environment have not been well studied. In fact, the uppermost layers of soil may affect the oral ingestion or re-suspension of fine soil particles in urban sites.

In addition to soil and dust, biological materials, such as fungi, lichens, grasses, tree bark, and the leaves of higher plants, have also been widely used to detect the deposition, accumulation, and distribution of metal pollution [10–12]. In comparison with soils, which can record anthropogenic inputs of metals for a period of several decades to several hundreds of years, biomaterial samples can only reveal a relatively short time-period of atmospheric metal deposition. Therefore, the combined use of these sample types may provide more precise and detailed information for assessing urban metal contamination and its possible effects on health. Furthermore, an understanding of the distribution of trace metals among these different urban components may facilitate the choice of appropriate and effective methods to investigate anthropogenic impacts on a given urban environment.

Guangzhou (GZ), the capital of Guangdong Province and the urban center of the Pearl River Delta (PRD) region, is one of China's largest industrial centers and as well as one of the most rapidly expanding cities in the country. In the last three decades, its rapid economic development has brought great prosperity to the region, but has also resulted in a wide range of environmental problems [13]. The aim of the present study is to study the rapid environmental changes in Guangzhou, using a combined sampling medium, including soil, soil dust, road dust, grasses, and tree leaves. The major objectives of the present research are as follows: (1) to study trace metal loadings in a typical urban environment; (2) to evaluate the relationship of trace metal distribution patterns among different urban components; and (3) to identify possible sources of trace metals in a typical urban environment.

1 Materials and methods

1.1 Study area and sample collection

Guangzhou City is located in southeast China (22°26′–23°56′N, 112°57′–114°03′E). Its climate is typical of subtropical humid monsoon regions, with an average temperature of 21.2–23.1°C and average annual rainfall of 1411–1942 mm [14]. At the end of 2009, the population numbered 1516 million in ten urban districts within an area of 3843 km^2 [14].

The study area is located in the western part of the city, and consists of typical industrial, commercial, and residential districts. A total of 22 sampling sites were selected in this area (Figure 1). Generally, only the uppermost layers of urban soils (e.g., 0–3 cm) can be re-suspended, and thereby affect inhalation and oral ingestion. But the degree of mixing in urban soils is very high; therefore, soils sampled at depths of 10 or 15 cm are often used for assessments of health and ecological risk [15]. The soil samples in this study were collected at two different depths of 0–3 cm (surface soil) and 0–15 cm (top soil), respectively. Each of the soil samples consisted of 9 sub-samples obtained in a 2 m × 2 m grid using a stainless steel hand auger. Soil dust samples were collected within the same area where the soils had been collected, and road dust samples were collected at the roadside near the soil sampling site. Both soil and road dust samples were collected using a vacuum cleaner equipped with stacked filters. The dust samples were then divided into four size fractions *in situ*: <50 μm, 50–100 μm, 100–250 μm, and 250–1000 μm. For the leaf and grass samples, these were collected from banyan trees (*Ficus microcarpa*) and manila grass (*Zoysia matrella*) respectively, as these are found throughout Guangzhou. Grass samples were collected only from the soil sampling sites. During sampling, the green parts of the sward were cut at about 2 cm above soil level with a stainless-steel knife. Tree leaves were collected from heights of 1.5 to 2 m, in order to achieve representative plant samples. Samples were taken from at least five trees in each sampling site. All of the samples were placed in polyethylene bags for transport and storage.

1.2 Sample preparation and analysis

The soil samples were dried in an oven at 60°C for 3 d. They then were crashed and sieved through a 1 mm polyethylene sieve to remove stones, coarse materials, and other debris. Soil/road dust were freeze-dried at −50°C, because these samples will undergo further examination to determine if organic pollutants (such as polycyclic aromatic hydrocarbons PAH) are present. The dried soil (~20 g) and

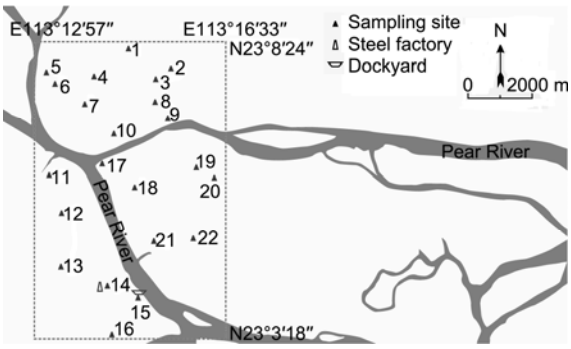

Figure 1 The study area and the sampling locations.

coarse dust (>100 μm) samples were ground in an agate grinder until fine particles (< 200 μm) were obtained. Each of the plant samples was divided into two parts: washed (by tap water and deionized water) and unwashed. Both the washed and unwashed plant samples were dried in an oven at 60°C for 3 d, and then ground into powder with a stainless steel coffee grinder. The prepared samples were then stored in polyethylene bags in a dessicator for further chemical analysis.

The ground soil (0.25 g), dust (0.10–0.20 g), and plant samples (1.0 g) were digested with concentrated HNO_3 and $HClO_4$ (4∶1) in an aluminum heating block [16,17]. The total concentrations of major elements (Ca, Mg, Fe, and Al) and trace metals (Co, Cu, Cr, Mn, Ni, Pb, and Zn) were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES, Perkin Elmer Optima 3300DV). Soil pH (H_2O) was determined in a soil to deionized water suspension of 1∶2.5 (w/v). For quality control, reagent blanks, replicates, and standard reference materials (SRM 2709 for soil, SRM 1648 for dust, and SRM 1515 and 1573a for plants), representing 10%, 20%, and 10% of the total sample population, respectively, were incorporated in the analysis to detect contamination and to assess the precision and bias of the analytical program. The recovery rates for most elements in the standard reference materials were around 78%–120%, but only 42%–63% for Al due to the absence of HF in the digestion process.

1.3 Statistical analysis

The data were statistically analyzed using the statistical package SPSS v13.0 (SPSS Inc.). A one-way ANOVA test (P<0.05) was used to analyze the variance in metal concentrations among different sampling sites. Paired-sample t-tests were employed to examine the differences in mean metal concentrations between different sample compartments. The correlation analysis was conducted using a Pearson correlation, and the level of significance was set at P<0.05 and P<0.01 (two-tailed).

2 Results and discussion

2.1 Metal concentrations

(1) Soils. The concentrations of trace metals (Co, Cr, Cu, Ni, Pb, and Zn), as well as pH value, in surface and top soils are listed in Table 1. There were no significant differences (P>0.05) in these chemical properties between surface soils (0–3 cm) and top soils (0–15 cm), with the exception of Cr and pH (P<0.05), indicating the generally uniform distribution of trace metals within the top soil layer of 0–15 cm. However, a few sites showed metal concentrations in surface soils that were notably higher than those in the top soils. For example, the concentrations of Cu, Pb, and Zn in the surface soil of Site 20 exceeded their corresponding concentrations in the top soils by 11, 3, and 6 times, respectively, indicating a site-specific source of pollution. The common enrichment of Cr in surface soils might suggest an enhanced input of Cr from non-point sources in recent years. The significantly lower pH of surface soils than top soils was probably due to the common occurrence of acid rain in the PRD region [18]. The highest concentrations of Cr (287 mg/kg) and Zn (787 mg/kg) were generally found in an industrial region (Site 14, near the GZ steel factory). However, the highest concentrations of Cu (246 mg/kg) and Pb (195 mg/kg), and the second-highest concentration of Zn (471

Table 1 Summary of metal concentrations and pH of surface soils and top soils from Guangzhou and other Chinese cities

		Co	Cr	Cu	Ni	Pb	Zn	pH
Surface soils (n=22)	Mean±SD	7.01±1.86	58.1±56.1	57.6±44.7	20.6±6.6	70.3±47.3	196±162	7.24±0.77
	Median	7.02	42.2	45.6	19.4	55.2	148	7.45
	Range	3.21–10.7	21.1–287	15.3–193	11.7–44.8	21.7–179	54.4–787	5.12–8.23
Top soils (n=22)	Mean±SD	6.28±1.58	39.1±22.4	47.3±50.3	18.5±3.70	67.9±55.2	155±122	7.60±0.85
	Median	6.48	34.1	40.0	18.6	42.7	117	7.79
	Range	2.97–9.35	18.8–115	8.74–246	12.5–28.3	20.4–195	40.4–512	4.54–8.72
Guangzhou								
Urban soil (2007) [19]				62.6	25.7	109	169	
Urban soil (2001) [20]			87.7	24.3	17.3	63.9	121	
Suburban soil [20]			16.1	2.3	26.3	55.1	108	
Background soil [21]		6.3	39	10.4	12.3	41	58	
PRD natural soil [22]		7.12	51.8	16.5	16.5	29.9	50.7	
Beijing [23]			60.3	34.4	25.9	39.5	89.6	
Shenyang [24]				51.3		75.3	138	
Xiamen [25]		4.1 (3.7)[a)]	14 (13)	26 (18)	8.4 (6.7)	36 (25)	100 (95)	
Yibin [26]				56.4 (51.6)		61.2 (46.8)	139 (112)	
Hong Kong [28]		3.4	16.2	29	5.4	149	166	

a) Data in bracket is the median value.

mg/kg) were found within an urban park (Site 5), which might indicate that the park had previously been used in another capacity. Lu et al. [19] also reported that soils in urban parks of this city had the highest mean concentrations of Cu, Ni, and Pb. Relatively low concentrations of trace metals were often found in areas with a very low density of traffic (e.g., Sites 7 and 16).

In comparison with previous studies conducted in the same city (Table 1), the concentrations of common trace metals in top soils were higher than those reported in 2001 [20], but lower than the values obtained five years ago [19]. In addition, the concentrations of trace metals were notably higher than those in the suburban soil [20] and the background soil from Guangzhou City [21], and in the natural soil from the PRD region [22]. Furthermore, the concentrations of Co, Cr, and Ni in this study were very similar to the levels that had been reported in 2001 and five years ago [19, 20]. Trace metal concentrations in urban soils of some Chinese cities published recently (since 2010) are also listed in Table 1. The results in our current study at Guangzhou are comparable with these data. The only exception is that Pb concentrations in the present Guangzhou study are much lower than those from Hong Kong.

(2) Dust. A similar pattern was seen in the grain size distribution of soil dust and road dust, with fractions of 100–250 μm dominating (~40% of the total mass) (Figure 2). The coarse fractions (>100 μm) of road dust were slightly higher than those of soil dust, while the fine fractions (<100 μm) were lower than those for soil dust.

It is a common phenomenon that metal concentrations generally increase as grain sizes in soil and dust decrease [9, 27–30]. With regard to soil dust, the concentrations of Cu, Pb, and Zn increased gradually as grain sizes decreased, while obvious increases in Cr and Ni were only found from 100–250 μm to 50–100 μm fractions (Table 2). Cobalt in soil dust was uniformly distributed in these grain fractions. Compared to soil dust, metal concentrations in road dust were much higher, and all of the metals exhibited a trend of dramatic increase as grain sizes decreased (Table 2). Generally, the smallest particles (<50 μm) of both soil and road dust had the highest concentrations of trace metals. This may be due to the fact that smaller particles have more specific surface sites for the adsorption or coating of trace metals [27]. In addition, anthropogenically emitted metal-embedded particles are normally in small size fractions. Adachi and Tainosho [31] reported that brake dust contains metal particles, such as Fe, Cu, Zr, Sb, and Ba, with a particle diameter of about 1 μm. Yellow paint contains Cr/Pb particles of about 0.5 μm. Tire treads have multi-angular ZnO particles of 1 μm or less in diameter [31]. Zhao et al. [30] also found that the smallest particles (< 44 μm) of road dust from Beijing had the highest metal concentrations. However, the concentrations of Cr, Cu, Pb and Zn for < 44 μm grain (75.5, 113, 112 and 591 mg/kg, respectively) in their study were much lower than our results for <50 μm grain.

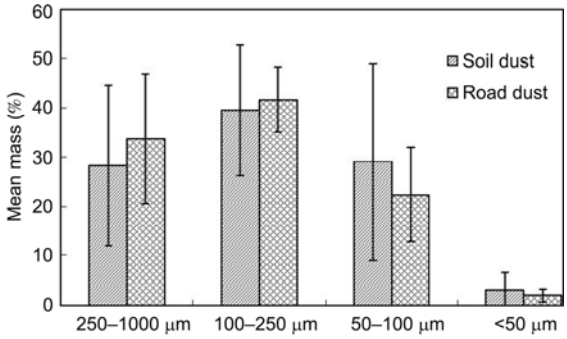

Figure 2 Grain size distribution of road and soil dust.

Since anthropogenic metals tend to be concentrated in fine particles, the concentrations of trace metals in the smallest grain fraction (<50 μm) of dust would best reveal the environmental conditions of the location where the sample was collected. High concentrations of trace metals in the <50 μm fraction of road dust were generally found in industrial areas (e.g., Site 14, the GZ steel factory; Site 15, the GZ dockyard), and moderately high concentrations of metals were observed in the sampling locations adjacent to busy roads (e.g., Sites 9 and 10). The lowest metal concentrations were consistently found in the samples collected from side roads (e.g., Sites 16 and 7) where the density of traffic was low.

(3) Tree leaves and grasses. The concentrations of trace metals in the plant samples exhibited narrow ranges, and were found in notably lower levels than those in the soil and dust samples (Table 3). For unwashed tree leaves, the concentrations of Pb varied most greatly (11 times), from 1.31 to 14.0 mg/kg, followed by Cr (7 times) from 0.77 to 5.12 mg/kg. Copper, Ni, and Zn concentrations varied about two times, from 6.81 to 15.6 mg/kg, 0.84 to 2.09 mg/kg, and 17.4 to 42.9 mg/kg, respectively. When compared with the data in tree leaves of the same species collected at the same sampling sites (Sites 8, 9, and 14) ten years ago (Figure 3) [32], the concentrations of Pb in the present study had significantly decreased, probably revealing reduced emissions of Pb in recent years due to the use of lead-free petrol in Guangzhou since 2000. In comparison with metal concentrations from the unwashed leaf samples, about 65%–99% of Cr, 29%–72% of Ni, 18%–49% of Cu, 35%–76% of Pb, and 7.5%–48% of Zn were removed by the washing process, indicating that a substantial amount of the metals in the tree leaves were present as particles adhering to the surface of the leaves rather incorporated in plant tissues. Al-Khashman et al. [10] studied metal retention in date palm leaves from urban areas, and found that metals were removed from leaves through washing at rates of 16%, 24%, 28%, 61%, and 25% for Cr, Cu, Ni, Pb, and Zn, respectively. Similarly, the removal of Cu, Pb, and Zn from leaves of *Robinia pseudoacacia* located in an urban-industrial zone were 17%–83%, 13%–56%, and 15%–74%, respectively [12].

Table 2 Summary of metal concentrations in different particle sizes of soil/road dust

		Co	Cr	Cu	Ni	Pb	Zn
Soil dust (*n*=7)							
250–1000 μm	Mean±SD	4.43±3.51	44.7±24.4	46.3±28.6	15.9±8.13	49.7±28.2	164±93.2
	Median	2.87	40.6	42.6	13.9	36.3	143
	Range	1.24–11.0	16.1–91.1	14.9–89.7	7.08–32.9	22.1–96.7	54.2–328
100–250 μm	Mean±SD	4.78±2.63	57.1±26.3	58.4±32.2	17.3±6.7	76.1±36.2	230±121
	Median	3.70	54.2	46.8	15.4	75.7	217
	Range	3.13–10.4	27.4–110	29.4–113	11.6–31.6	38.7–135	106–483
50–100 μm	Mean±SD	5.61±1.80	78.8±13.4	99.4±34.1	21.8±4.4	98.6±26.1	344±69
	Median	5.66	81.7	93.4	22.2	111	340
	Range	3.23–7.77	50.6–91.3	50.4–154	15.2–28.3	52.3–125	210–426
<50 μm	Mean±SD	4.27±1.85	77.2±14.4	163±45.7	22.4±3.55	114±33.6	366±69.8
	Median	4.55	70.4	171	22.8	115	366
	Range	1.61–6.27	61.3–98.8	103–223	17.4–28.2	69.4–156	273–467
Road dust (*n*=22)							
250–1000 μm	Mean±SD	2.81±2.21	36.0±20.3	68.9±79.2	9.39±3.56	40.5±22.4	196±139
	Median	2.44	30.6	43.1	8.83	41.5	172
	Range	nd [a)]–9.25	12.1–94.0	16.7–362	5.12–16.4	11.5–82.5	86.8–765
100–250 μm	Mean±SD	3.89±2.05	74.2±29.3	193±204	21.6±9.03	104±86.8	390±181
	Median	3.27	72.6	114	19.3	83.4	353
	Range	1.26–9.55	37.4–142	31.7–798	5.94–40.7	29.5–412	108–1040
50–100 μm	Mean±SD	6.31±2.09	138±44.3	250±149	37.2±14.5	162±96.8	739±313
	Median	6.06	122	212	34.2	141	641
	Range	3.12–10.9	71.1–248	74.9–796	12.8–75.6	77.7–532	257–1560
<50 μm	Mean±SD	8.87±4.28	176±63	376±227	48.3±16.1	406±694	1150±606
	Median	9.66	174	337	47.5	243	1120
	Range	1.77–16.7	57.7–302	134–1260	16.1–74.5	103–3470	322–3250

a) nd, non-detectable.

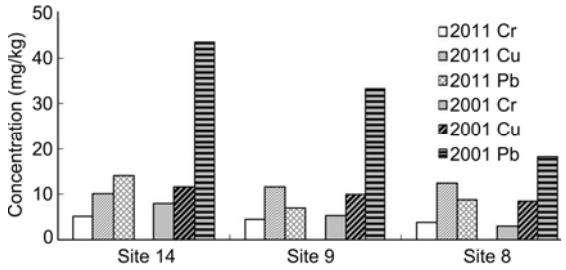

Figure 3 Comparison of Cr, Cu, and Pb concentrations of tree leaves between 2011 and 2001.

Our results were similar (Cu, Pb, and Zn) or higher (Cr and Ni) than the levels observed from these two plants, which had been considered by the authors to be suitable indicators of air pollution. This shows that the plant *Ficus microcarpa* would be an ideal bioindicator of airborne metal pollution in the urban areas of this region.

In comparison with tree leaves, the variations in metal concentrations of the grass samples were smaller, from two (Cu) to five times (Pb). However, the concentrations of Cr, Ni, and Zn in the grass samples were significantly higher (P<0.05) than those in the tree leaves. The differences in metal concentrations between unwashed and washed grasses were not as significant as those for the tree leaves. Washing can remove only 19% of Pb, and 7.2% of Zn, and no significant amounts of Cr, Cu, and Ni from the grasses.

The spatial distribution patterns of trace metals in the tree leaves were similar to those of the road dust. High concentrations of metals were found in the industrial area (Site 14, the GZ steel factor), and low concentrations were observed in the urban park away from the main roads (Site 4). However, these distribution patterns for grass samples were not as notable as those for the tree leaves.

2.2 Relationships between metal concentrations

The results of the correlation analysis of metal concentrations for soil, soil dust and road dust, and tree leaf and grass samples are presented in Tables 4–6, respectively. Strong correlations between metals were found in surface soils, while the correlations were less significant for top soils

Table 3 Summary of metal concentrations of tree leaves and grasses [a)]

		Cr	Cu	Ni	Pb	Zn
Tree leaves (*n*=21)						
Unwashed	Mean±SD	2.99±1.05	11.0±2.5	1.50±0.36	6.72±3.47	28.7±8.1
	Median	2.97	10.8	1.52	5.52	28.2
	Range	0.77–5.18	6.81–15.6	0.84–2.09	1.31–14.0	17.4–42.9
Washed	Mean±SD	0.38±0.40	6.96±1.20	0.67±0.22	2.96±1.79	20.0±4.17
	Median	0.28	7.00	0.67	2.89	19.3
	Range	nd [b)]–1.51	4.64–9.32	0.41–1.29	0.59–7.78	13.3–28.9
Grasses (*n*=20)						
Unwashed	Mean±SD	26.4±11.8	12.1±2.3	12.0±5.5	5.47±2.75	50.7±10.0
	Median	23.0	11.6	10.4	4.34	52.2
	Range	14.8–59.6	6.97–17.0	7.06–268	2.84–13.3	26.8–70.3
Washed	Mean±SD	22.0±7.47	12.5±2.2	11.5±3.5	4.43±2.43	47.3±8.7
	Median	21.4	12.5	10.5	3.31	48.0
	Range	11.0–34.3	7.82–15.8	6.89–19.6	2.08–10.2	29.3–60.3

a) Cobalt concentrations are not listed because many of them were below the detection limit; b) nd, non-detectable.

(Table 4). For soil dust, significant correlations of metals were mainly found in coarse fractions (>100 μm). For road dust, such relationships were generally observed in fine fractions (<100 μm) (Table 5). The results indicated that trace metals in finer particles of road dust had more likely been influenced by the same sources (e.g., vehicle related emissions), while for metals in coarser fractions, the sources may have been more diverse; and vice versa for soil dust. For plant samples, the correlations of metals in tree leaves were more significant than those in grass samples (Table 6). The diverse relationships among trace metals may reveal the different loadings of metal pollutants into distinguished environmental compartments (receptors) in urban environments.

2.3 Relationships of metals between sample types

(1) Correlation between tree leaves and road dust. A correlation analysis showed that concentrations of Pb in the smallest particles of dust (<50 μm) were significantly correlated to the Pb in tree leaves (Figure 4), suggesting that local traffic emissions were the main source of the Pb that had accumulated on the tree leaves, since metals concentrated in road dust are mainly derived from traffic-associated particles [33]. The three sampling sites close to industrial facilities, including the GZ dockyard (Site 15), the GZ cotton mill (Site 21), and a hardware market (Site 22), all had high concentrations of Pb in road dust, and relatively low concentrations of Pb in tree leaves, and thus were away from the linear trend of the majority of the samples (Figure 4). This result reflected the different responses between road dust and tree leaves to the Pb emitted from these industrial facilities.

With the exception of Pb, significant correlations between road dust and tree leaves were not found for other metals, which suggest that these metals in tree leaves came not only from local road-traffic sources, but also from non-traffic pollutants in the wider urban area. It was

Table 4 Pearson correlation coefficients (*r*) of trace metals in surface soils and top soils

	Co	Cr	Cu	Ni	Pb
Surface soils (*n*=22)					
Cr	0.319				
Cu	0.353	0.501*			
Ni	0.744**	0.307	0.708**		
Pb	0.046	0.476*	0.721**	0.186	
Zn	0.178	0.922**	0.671**	0.268	0.715**
Top soils (*n*=22)					
Cr	0.326				
Cu	0.073	0.549**			
Ni	0.465*	0.371	0.600**		
Pb	0.036	0.398	0.785**	0.229	
Zn	0.063	0.774**	0.647**	0.185	0.609**

*P<0.05, **P<0.01 (two-tailed).

Table 5 Pearson correlation coefficients (r) of trace metals in soil dust and road dust

	Co	Cr	Cu	Ni	Pb		Co	Cr	Cu	Ni	Pb
Soil dust (n=7)						Road dust (n=22)					
250–1000 μm						250–1000 μm					
Cr	0.950**					Cr	0.647**				
Cu	0.683	0.768*				Cu	0.399	0.525*			
Ni	0.941**	0.972**	0.802*			Ni	0.233	0.309	0.085		
Pb	0.930**	0.918**	0.867*	0.900**		Pb	0.102	0.280	0.336	0.519*	
Zn	0.938**	0.959**	0.881**	0.944**	0.986**	Zn	0.670**	0.722**	0.784**	0.172	0.241
100–250 μm						100–250 μm					
Cr	0.876**					Cr	0.551**				
Cu	0.723	0.921**				Cu	0.363	0.452*			
Ni	0.906**	0.988**	0.914**			Ni	0.269	0.476*	0.231		
Pb	0.745	0.911**	0.985**	0.891**		Pb	0.554**	0.166	0.223	0.258	
Zn	0.901**	0.964**	0.878**	0.964**	0.874*	Zn	0.775**	0.600**	0.741**	0.349	0.518*
50–100 μm						50–100 μm					
Cr	0.458					Cr	0.633**				
Cu	0.363	0.703				Cu	0.613**	0.506*			
Ni	0.644	0.783*	0.830*			Ni	0.633**	0.566**	0.703**		
Pb	0.805*	0.787*	0.757*	0.871*		Pb	0.589**	0.378	0.834**	0.527*	
Zn	0.327	0.916**	0.628	0.585	0.741	Zn	0.746**	0.402	0.708**	0.481*	0.696**
<50 μm						<50 μm					
Cr	0.406					Cr	0.730**				
Cu	-0.065	0.615				Cu	0.451*	0.657**			
Ni	0.764*	0.427	0.155			Ni	0.771**	0.716**	0.479*		
Pb	0.690	0.743	0.628	0.599		Pb	0.504*	0.521*	0.896**	0.351	
Zn	0.671	0.817*	0.465	0.712	0.894**	Zn	0.705**	0.667**	0.754**	0.500*	0.813**

*P<0.05, **P<0.01 (two-tailed).

Table 6 Pearson correlation coefficients (r) of trace metals in unwashed tree leaves and grasses

	Cr	Cu	Ni	Pb
Tree leaves (n=21)				
Cu	0.539*			
Ni	0.727**	0.634**		
Pb	0.737**	0.468*	0.480*	
Zn	0.712**	0.658**	0.657**	0.644**
Grasses (n=20)				
Cu	0.413			
Ni	0.991**	0.440		
Pb	–0.042	0.112	–0.132	
Zn	0.526*	0.504*	0.525*	0.109

* P<0.05, ** P<0.01 (two-tailed).

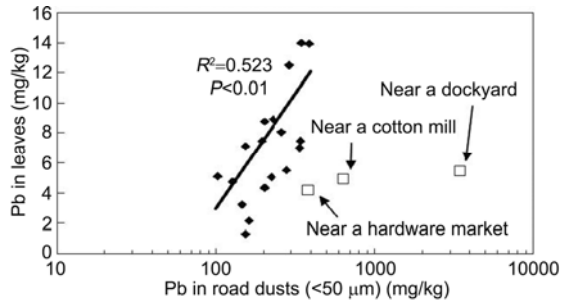

Figure 4 Correlation of Pb concentrations between road dusts (<50 μm) and tree leaves.

reported that the majority of particles observed on tree leaves belonged to a class of fine particles (<2 μm) [34]. The fine particles, such as PM_{10}, from the roadside had come from both urban sources and local traffic emissions [33].

(2) Correlation between soils and soil dust. There were no significant correlations of metal concentrations between soils (both surface soils and top soils) and overall soil dust (the sum of the metal concentrations in each fraction multiplied by its mass percentage). However, the Co and Ni in the fraction of 50–100 μm of soil dust were significantly correlated to those in surface soils (Figure 5), which suggests that the Co and Ni in the soil dust (50–100 μm) were mainly derived from soil materials. The concentrations of these two metals in both soils and soil dust were similar to the background values, reflecting their geogenic origin. The absence of correlations for other metals indicated that these metals (Cr, Cu, Pb, and Zn) in soil dust had not originated predominantly from the soils. Soil dust is situated at the air-soil interface so it acts as a link between the atmosphere and soil. The present study confirmed that metals in the soil dust were partially derived from soils and partially from atmospheric deposition (e.g., local traffic and urban-wide deposition). Furthermore, the relationships of trace metals between soil dust and surface soils indicated that surface soils (0–3 cm) could reflect the conditions of both atmospheric deposition and soil materials. However, soils in the top 15 cm may not effectively reveal airborne trace metal

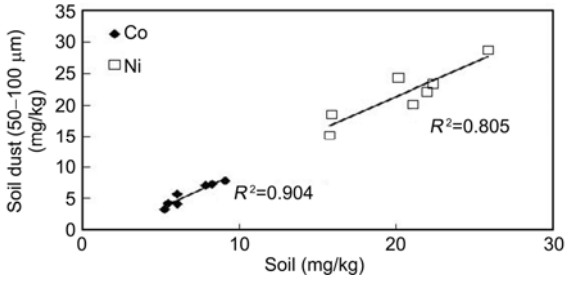

Figure 5 Correlations of Co and Cr concentrations between surface soils and soil dust (50–100 μm).

pollution. It is well known that trace metals are present in soils in different chemical forms, and vary widely in solubility or bioavailability [2]. Generally, metals derived from anthropogenic sources have a relatively higher degree of bioavailability than those from natural sources (soil materials) [2,35]. Therefore, the difference in metal origins among soil dust, surface soils, and top soils can induce different outputs in terms of risk assessment, despite the fact that they have similar total metal concentrations.

3 Conclusions

An integrative investigation of trace metal (Co, Cr, Cu, Ni, Pb, and Zn) contamination in different sample matrices, including soils, dusts, and plants, were conducted in a typical urban area of Guangzhou City. The concentrations of trace metals varied greatly among different sample types. Surface soils had metal concentrations similar to those of top soils. In the case of road and soil dust, trace metals had a tendency to concentrate in fine particles (<100 μm). There were significant differences in metal concentrations between unwashed and washed tree leaves, while the differences between unwashed and washed grass samples were not significant. The overall trend in the distribution of metals among different samples was generally as follows: road dust > soil dust $\geqslant$ surface soils $\approx$ top soils > grasses $\geqslant$ tree leaves. The spatial distribution patterns of trace metals indicated that industrial activities and traffic emissions were the major sources of metal contaminants in the urban environment of Guangzhou. The trace metals exhibited different combination features among different samples, indicating different loadings of trace metals among sampling types. Significant correlations of metal concentrations were found between tree leaves and the smallest (<50 μm) fraction of road dust, and between soil dust (50–100 μm) and surface soils, suggesting that the trace metals in these samples may influence each other. Our results in the present study provided useful information about interrelationships in integrated environmental compartments in urban areas.

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