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ORIGINAL PAPER

Threat of heavy metal contamination in eight mangrove plants from the Futian mangrove forest, China

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Abstract Mangrove plants play an important role in heavy metal maintenance in a mangrove ecosystem. To evaluate the characteristics of heavy metal contamination in the Futian mangrove forest, Shenzhen, China, eight heavy metals in mangrove sediments and plants were monitored, including essential elements such as Cu and Zn, and non-essential elements such as Cr, Ni, As, Cd, Pb and Hg. The results showed that the heavy metals exhibited the following scheme: Zn $>$ As $>$ Cu $\approx$ Cr $>$ Pb $>$ Ni $>$ Cd $\approx$ Hg in sediment cores, among which Cd, As, Pb and Hg contents were nearly ten times higher than the background values. There was no significant difference in metal maintenance capability between native and exotic species. In mangrove plants' leaves and stems, concentrations of Cu, Zn and As were higher than other heavy metals. The low bioconcentration factors for most heavy metals, except for Cr, implied the limited ability of heavy metal accumulation by the plants. Mangrove plants seem to develop some degree of tolerance to Cr. The factor analysis implies that anthropogenic influences have altered metal mobility and bioavailability.

Keywords Mangroves · Heavy metals · Bioaccumulation · Sediments

Introduction

Mangrove forests, complex intertidal ecosystems, are located at the interface between marine and terrestrial environments in the tropics and subtropics covering 15 million hectares in 121 countries (Agoramoorthy et al. 2008; Lewis et al. 2011). Mangrove forest ecosystems provide diverse ecological benefits, including flood protection, shoreline erosion prevention, salinity buffering and biodiversity promotion by offering habitats for some other plants grown in mangrove forests, crustaceans or birds (Rönnbäck et al. 1999; Lewis et al. 2011). In addition, mangrove plants' special capability of surviving in high-salt and anoxic conditions and high tolerance to heavy metal stress (Alongi et al. 2004) contribute to their potential use in preventing dispersion of anthropogenic pollutants into aquatic ecosystems (Yang et al. 2008). In spite of their importance, mangrove ecosystems have suffered significant anthropogenic contaminant inputs due to their location close to urban development (MacFarlane

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et al. 2007), among which the majority are heavy metal pollutants (MacFarlane 2002).

Since recent decades, the rapid urbanization and industrialization have brought serious ecological stress to mangrove ecosystem fringed the south coast of China, resulting in a loss of 66 % of mangrove forests (Li and Lee 1997). As an important habitat for many rare wild birds, especially migratory birds, the Futian mangrove forest has received extensive attention (Zan et al. 2003; Wang and Lin 1998; Wang et al. 1999).The Futian mangrove forest is the rare coastal mangrove wetland located in the hinterland of the modern metropolis in China. Since it is located in Shenzhen Bay, which is the reservoir of domestic sewage from Shenzhen and Hong Kong, this area differs from other mangrove wetlands less disturbed by anthropogenic activities (Xie et al. 2010). Compared to the results in Fujian (Vane et al. 2009) and Hainan (Qiu et al. 2011), our findings in Shenzhen indicate a higher metal contamination level in sediments. Lin et al. (1997) reported heavy metal contents in surface sediments in *Avicennia marina* community of Futian mangrove, like Cu, Zn, Cr, Ni and Pb, and Wang et al. (2003a, b) focused on S*onneratia apetala, S. caseolaris and Kandelia candel community*. Despite the difference with the community, the metal accumulation increased significantly with time. To date, it is lack of the systematic examination of metal accumulation in surface sediments in cross-species communities. The overall contamination level is not clear.

Mangrove plants absorb and store heavy metals mainly in roots and still transport a part upward into sensitive tissues: Metal concentrations in shoots appear to be half that of roots or lower (Zhou et al. 2011; MacFarlane et al. 2007). Previous cultivation experiments have proved that excessive essential metal elements and non-essential elements could affect the growth (Cox and Hutchinson 1981), metabolism activities (Gu et al. 2002) and cell structure (Wang et al. 2003a, b) of plants. For mangrove species, Cd stress reduced the root biomass of *K. candel* seedlings and Zn stress increased their taproot (Guo 2009). Cr stress limited the height of *A. marina* seedlings, and also the chlorophyll contents in leaves (Fang et al. 2008). The shoots are vulnerable to metal stress. In Futian mangrove forest, the native species *Acanthus ilicifolius*, *A. marina* and *K. candel* are the dominant species. In 1993, exotic mangrove species, *S. apetala* and *S. caseolaris*, were introduced into this area to improve the local mangrove biodiversity and ecological balance. Growing in the moderately contaminated sediments, both native and exotic mangrove species show high tolerance to heavy metal stress. The migration, accumulation and circulation of metal pollutants in several mangrove species have been investigated (Zhang et al. 2001; Xie et al. 2010). In order to better understand the metal stress posed to mangrove plants, an overall examination is essential about the metal bioaccumulation in shoots of the Futian mangrove species involving typical native and exotic mangrove species.

The objectives of this study were as follows: (1) to find out the background metal accumulation in cross-species communities by investigating the current metal contents in surface sediments: copper (Cu), zinc (Zn), chromium (Cr), nickel (Ni), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg); and (2) to reveal the metal stress posed to mangrove plants by examining metal accumulation in typical species growing in a moderately contaminated mangrove ecosystem, including six native plants: *A. ilicifolius*, *A. corniculatum*, *A. marina*, *Bruguiera gymnorhiza*, *E. agallocha* and *K. candel*, and two exotic plants: *S. apetala* and *S. caseolaris*.

Materials and methods

Description of study area

Seedlings of eight mangrove plants were collected from the Futian Nature Reserve (22°31.56′N,114°00.40′E), Shenzhen, Guangdong Province, China, in May 2011. The reserve is located on the northeast coast (Fig. 1) of Shenzhen Gulf, with an area of 304 ha. The mean annual temperature is 23.0 °C, with the highest temperature in July (36.1 °C) and the lowest in January (3.9 °C). The mean annual precipitation is 1,935.8 mm mostly from May to September, and the mean annual relative moisture is 74 %. The tides in Shenzhen Bay are semidiurnal, with an average range of 1.9 m.

Sample collection, preparation and analysis

In May 2011, seedlings of eight mangrove species were collected with three replicates for each plant. The mangrove seedlings were as follows: six native species

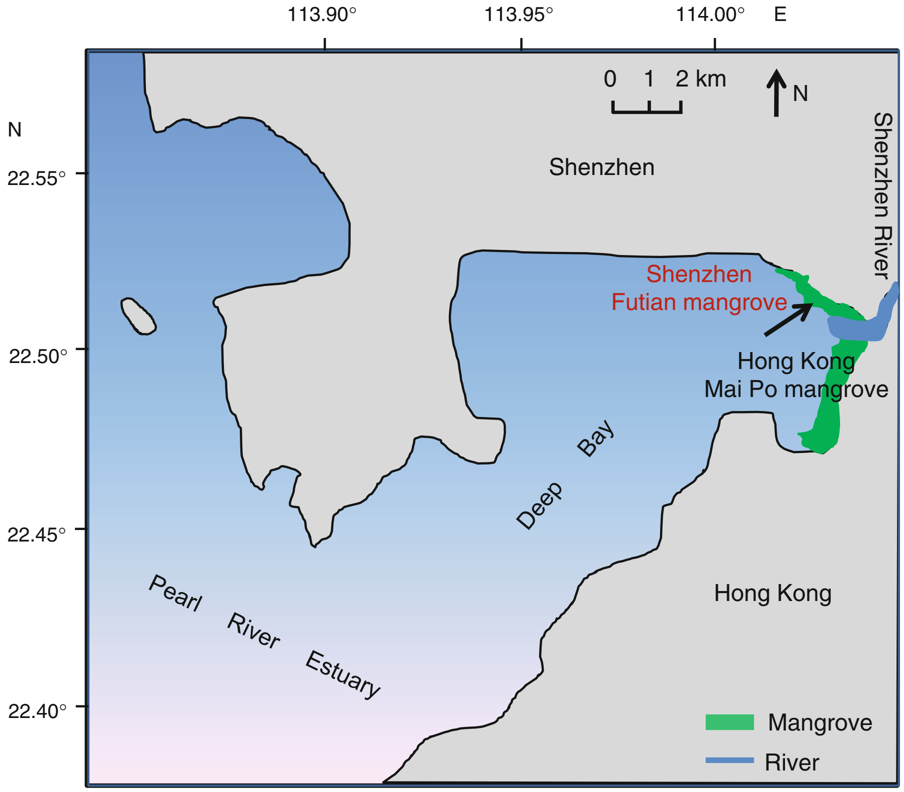

Fig. 1 The location of study area

including *A. ilicifolius, A. corniculatum, A. marina, B. gymnorhiza, E. agallocha* and *K. candel*, and two exotic species: *S. apetala* and *S. caseolaris*. Six native mangrove plants were located in the middle of intertidal zones, and two exotic plants grew on the offshore adjacent to a mudflat. Since the location might influence the metal accumulation, sampling sites were selected around the boundary zones in order to reduce the difference. In the native and exotic mangrove sampling sites, three sediment cores (0–30 cm depth) were also collected using acid-washed PVC pipes (150 cm length, 7.5 cm internal diameter), respectively. All sampled plants and sediment cores were immediately sealed with plastic bags and transported back to the laboratory on the same day.

The seedlings were washed with deionized water to remove the mud, then naturally dried for three days and heated in an oven at 80 °C for 24 h. Leaves and stems from each seedling were separated and grounded into fine powder, respectively. The sediment samples were dried at room temperature, sieved through a 1-mm sieve to reduce coarse particles and then separated. To analyze heavy metal concentrations, samples were digested referring to the standard methods of US EPA 3052. Plant samples were first mixed with 9 ml HNO_3 and 1 ml HCl and then subjected to microwave-assisted acid digestion. Sediment samples were subjected to microwave digestion in a mixture of 9 ml HNO_3, 3 ml HF and 1 ml HCl. All reagents were of analytical grade or better. The concentrations of essential (Cu, Zn) and non-essential (Cr, Ni, As, Cd, Pb) elements in plants and sediments were determined by inductively coupled plasma-mass spectrometer (ICP-MS). The Hg concentration was measured with ZYG-II cold vapor atomic fluorescence spectrometer (CVAFS).

The bioaccumulation of environmental pollutants was quantified by bioconcentration factors (BCFs) in order to estimate chemical residuals in plants (Mountouris et al. 2002). The bioconcentration factor is defined as $\mathrm{BCF} = C_{biota}/C_{soil}$, where C_{biota} is heavy metal concentration in plants (leaves or stems) and C_{soil} is heavy metal concentration in sediment.

Statistical analysis

Spearman's correlation analysis was performed to identify possible relationships between heavy metals. In order to understand the significant groups of studied heavy metals and the dominant processes by which metals were sourced in leaves and stems of mangrove plants, principal component analysis (factor analysis) extraction using varimax rotation scheme was performed. All statistical analyses were done through Statistical Product and Service Solutions (SPSS) 11.5 for Windows.

Results and discussion

Heavy metals in mangrove sediments

Table 1 shows that in both native and exotic mangrove sediments, Zn had the highest levels (358.5 and 252.0 μg g^{-1}), followed by As (171.7 and 150.0 μg g^{-1}), Cu (88.8 and 93.0 μg g^{-1}), Cr (96.2 and 81.0 μg g^{-1}), Pb (72.0 and 77.0 μg g^{-1}), Ni (44.6 and 45.0 μg g^{-1}), Cd (0.94 and 2.96 μg g^{-1}) and Hg (0.14 and 0.17 μg g^{-1}). The trend followed a distinctly similar pattern of $Zn > As > Cu \approx Cr > Pb > Ni > Cd \approx Hg$. It is reasonable that Zn, Cu, Cr and Ni concentrations were at a higher level because they were rich in soils. All the metal contents exceeded the background values (Gao et al. 1998), especially Cd, As, Pb and Hg, whose contents were approximately ten times higher than the background values. Comparing the mean values of the present results with those in other areas of China and throughout the world (Table 1), As and Cd possessed significantly higher concentrations (more than ten times), and other metals were moderately higher (less than ten times) as well. According to the classification system from the Hong Kong Environmental Protection Department (Tam and Wong 2000), the concentrations of Cu, Zn, Cr and Ni in both native and exotic species communities were in Class D, which represented serious contamination. Cd concentration in sediments of the native community could be classified as Class B and Pb was Class C, which meant it was slightly and moderately contaminated by Cd and Pb, respectively, while serious contamination was detected in the exotic community. Unlike that for other heavy metals, the

Table 1 Concentrations of heavy metals (μg g^{-1}) in mangrove sediments from China and other areas in the world

Areas	Cu	Zn	Cr	Ni	As	Cd	Pb	Hg
Native mangrove ecosystem[a]	88.8	358.5	96.2	44.6	171.7	0.94	72.0	0.14
Exotic mangrove ecosystem[a]	93.0	252.0	81.0	45.0	150.0	2.96	77.0	0.17
Shenzhen, Guangdong[k]	38.3	114	7.97	25	–	0.136	28.7	–
Shenzhen, Guangdong[l]	45.58	125.08	58.04	62.80	–	–	62.92	–
Xiamen, Fujian[b]	37.0	194.0	56.0	26.0	14.0	–	95.0	0.12
Haikou, Hannan[b]	27.0	92.0	122.0	54.0	13.0	–	33.0	0.06
Mai Po, Hong kong[c]	48–87	130–349	10–75	25–95	–	1.1–1.4	69–220	–
Sanya Bay, Hainan[d]	9.0	53.0	12.0	–	7.0	0.13	18.0	0.06
Yalong Bay, Hainan[d]	5.0	26.0	11.0	–	5.0	0.12	15.0	0.03
Dongzhai Haibor, Hannan[d]	18.0	57.0	40.0	–	13.0	0.11	19.0	0.08
Singapore[e]	7–32	51–120	17–32	7–12	–	0.18–0.27	12–31	–
Coast, Brazil[f]	98.6	483	42.4	–	1.3	1.32	106.8	–
Sirik Azini creek, Iran[g]	26–27	63–152	–	55–102	–	24–31	32–68	–
Andaman Island, India[h]	81–88	12–23	13–20	7–12		0.80–1.50	4–5	–
Sunderban mangrove, India[i]	11–59	28–108	27–87	11–43	3.6–18.3	0.12–0.21	17–34	–
Cross River Estuary, Nigeria[j]	24–34	140–189	20–27	15–30	–	–	9–25	–
The continental crust[m]	32	70	80	38	4.4	0.079	1.46	0.013

[a] The present study; [b] Vane et al. (2009), [c] Ong Che (1999), [d] Qiu et al. (2011), [e] Cuong et al. (2005), [f] Kehrig et al. (2003), [g] Parvaresh et al. (2011), [h] Nobi et al. (2010), [i] Chatterjee et al. (2009), [j] Essien et al. (2009), [k] Lin et al. (1997), [l] Wang et al. (2003a, b), [m] Gao et al. (1998)

data for Hg concentrations in a mangrove system have not been fully documented. In the present study, Hg levels in surface sediments (0.14 and 0.17 μg g^{-1}) were higher than those in Hong Kong (Ong Che 1999), Fujian (Vane et al. 2009) and Hainan (Qiu et al. 2011) mangrove areas, with mean concentrations lower than 0.12 μg g^{-1}. Compared with the previous study in exotic species community (Wang et al. 2003a, b), the metal concentrations in the present study have generally risen to a higher degree. The data of native species community in Table 1 were the average of the six native species community and were also higher than the previous study (Lin et al. 1997).

Heavy metals in mangrove plants

Heavy metal accumulations in leaves and stems of eight mangrove species are shown in Table 2. There were obvious interspecies and tissue differences among eight metals in mangrove plants. As essential metals for plant growth, Cu plays an important role in enzymatic activities of oxidative reduction, and Zn is crucial for plant nutrition and enzymatic activities (Kabata-Pendias and Pendias 1993; Bonanno and Giudice 2010). In both leaves and stems, levels of Cu and Zn were significantly higher than other elements except for Cr, since they were essential elements for plant growth (Table 2). Cu concentrations were lower than the phytotoxic range (25–40 μg g^{-1}), except for stems of *A. ilicifolius*; Zn were also not in the phytotoxic range (500–1,500 μg g^{-1}) (Chaney 1989).The concentrations of Cu and Zn in leaves did not change significantly when compared with what Zan et al. (2002) found in leaves of *K. candel*, *S. apetala* and *S. caseolaris*, indicating that the accumulation of Cu and Zn in mangrove remained stable, not easily affected by increasingly severe pollution. It was also noteworthy that levels of Cu and Zn in exotic *S. apetala* and *S. caseolaris* were higher than in native mangroves, in particular with *A. marina*, *B. gymnorhiza* and *K. candel*. The higher contents of Cu and Zn partly resulted from faster growth of exotic *S. apetala* and *S. caseolaris* when initially introduced into the Futian mangrove forest in 1993 from Dongzhaigang, Hainan. No similar trends were detected for most non-essential heavy metals.

Table 2 Heavy metal concentrations in leaves and stems of mangrove species

Plant species	Structures	Essential elements		Non-essential elements					
		Cu	Zn	Cr	Ni	As	Cd	Pb	Hg
A. ilicifolius	Leaves	10.12	173.14	77.56	1.41	2.50	0.045	1.44	51.02
A. corniculatum	Leaves	2.66	40.93	75.98	0.48	2.01	0.021	0.75	50.34
A. marina	Leaves	6.57	50.55	80.87	0.88	2.08	0.022	0.87	55.39
B. gymnorhiza	Leaves	4.46	27.35	88.25	1.18	1.58	0.034	0.53	25.61
E. agallocha	Leaves	5.89	87.36	87.80	1.41	2.43	0.092	1.14	97.12
K. candel	Leaves	3.40	38.09	76.66	0.98	2.30	0.046	0.44	9.58
S. apetala	Leaves	13.06	69.50	70.26	1.09	1.96	0.023	0.84	23.33
S. caseolaris	Leaves	15.04	71.64	72.37	0.80	1.71	0.035	0.44	36.42
A. ilicifolius	Stem	30.89	79.97	98.88	1.20	1.62	0.030	0.61	0.35
A. corniculatum	Stem	7.42	64.84	96.10	0.61	2.27	0.022	0.93	1.03
A. marina	Stem	7.12	57.12	99.59	0.77	1.70	0.026	0.85	0.21
B. gymnorhiza	Stem	8.95	43.11	106.04	1.01	1.53	0.178	0.41	2.05
E. agallocha	Stem	11.33	64.24	101.41	1.92	1.63	0.249	0.76	2.29
K. candel	Stem	5.18	27.46	97.49	0.90	2.80	0.058	0.31	2.14
S. apetala	Stem	16.40	86.23	88.98	1.16	1.89	0.141	1.25	6.34
S. caseolaris	Stem	15.88	59.17	92.86	0.82	1.71	0.060	0.47	2.80

Results are based on 1 g dry samples and are means of three duplicates. The unit of C_{Hg} is ng/g, and for other metals, it is μg/g

Cr is a non-essential element and toxic to plant growth (Bonanno and Giudice 2010). When mangrove plant seedlings exposed to excessive Cr in surroundings, their roots would be shorten, height would be limited, biomass would be lower and chlorophyll contents would be inhibited (Fang et al. 2008). In this study, the mean concentration of Cr in mangrove plants was around 87 μg/g, which was remarkably out of the previous reported range of 0.28–0.73 μg/g (Lin et al. 1997). However, no apparent adverse effects were detected in this study, which may be due to mangrove's high tolerance to Cr stress. Cr concentration limit was 0.5 μg/g dry weight in plants in unpolluted environment (Allen 1989). Our finding was above that limit, showing the mangrove plants were growing in a metal-polluted environment. Sekomo et al. (2011) reported that Cr was easily taken up and translocated in *Cyperus papyrus*. The high Cr accumulation observed in shoots of mangrove plants suggested Cr was easily taken up. But mangrove plant stems accumulated more Cr than leaves, showing the relatively weak Cr translocation ability.

Hg, a contaminant of great concern, can become phytotoxic as its bioavailability increases (Bargagli 1998). Thus, Hg and its compounds, such as methylmercury (MeHg), can harm human beings through the food chains (Louis et al. 1996; Ding et al. 2009). Plant uptake of Hg plays an important role in the Hg biogeochemical cycle, which is dependent on plant species and age, as well as atmospheric Hg concentrations (Ding et al. 2010; Ferrara et al. 1991; Guentzela et al. 1998). Ding et al. (2010) found that Hg concentrations in five mangrove species were greater in stems than in leaves. In contrast, Hg accumulations in plants from a landfill decrease from leaves to stems (Ding et al. 2007). In the present study, Hg concentrations in leaves were significantly higher than in stems, in both exotic and native plant species, indicating higher translocation capacity of Hg from stems to leaves. Another possible hypothesis may be that mangrove can also derive amounts of Hg through foliar absorption in addition to root adsorption. In fact, the Futian mangrove forest is located a short distance away from the well-developed industrial area in Shenzhen, with the atmospheric Hg concentration reported to be as high as 62 ng m^{-3} (Ding et al. 2010).

According to the studies on leaf anatomy (Li and Lin 2006), differing leaf morphology features were observed between native and exotic species: Epidermal trichomes were located outside *S. apetala* upper and lower epidermis and *A. marina* lower epidermis while they were not observed on other native species such as *K. candel*, *A. corniculatum* and *A. ilicifolius*; stomatas distributed in both the upper and lower epidermis of *S. apetala* while only in the lower epidermis of native species. Such features might affect metal uptake and maintain process, which deserve to be investigated further.

Bioaccumulation of eight heavy metals

Metal exclusion and accumulation are two basic tolerance strategies of plants facing heavy metal stress (Dahmani-Muller et al. 2000). In this study, none of the mangrove plants showed heavy metal levels higher than 1,000 μg g^{-1} in leaves or stems (Table 2). In other words, none of them were hyperaccumulators (Baker and Brooks 1989). However, the ability of these plants to tolerate and accumulate heavy metals may be useful for phytostabilization. Generally, a plant's ability to accumulate metals from soils can be estimated using the BCF, which is defined as the ratio of metal concentration in plants to that in soil (Qiu et al. 2011; Agoramoorthy et al. 2008). The results of BCFs showed that leaf and stem BCFs for Cr were significantly higher than other heavy metals (Fig. 2), which may be related to preferable translocation and accumulation of Cr in the Futian mangrove forest. According to our results, BCFs for heavy metals (not Cr) were mainly lower than 1.00, implying that limited amounts of the metals were transferred to stems and leaves, thus guaranteeing conduction of various important metabolic activities including photosynthesis in the aerial parts. Hg in leaves exhibited a much higher BCF value than in stems, which is related to the special physiological structures of leaves. Actually, the distinct characteristic of leaves is the periclinal walls of epidermal cells surrounded by continuous thick keratose layers (Li and Lin 2006; Ding et al. 2010), contributing to prevention of water and Hg loss from the plant to the air.

Factor analysis

Even though the washout of rainfall (1,935.8 mm a^{-1}) rapidly transferred contaminants, relatively high accumulation occurred in mangrove ecosystem in Shenzhen Bay. To understand the significant groupings and

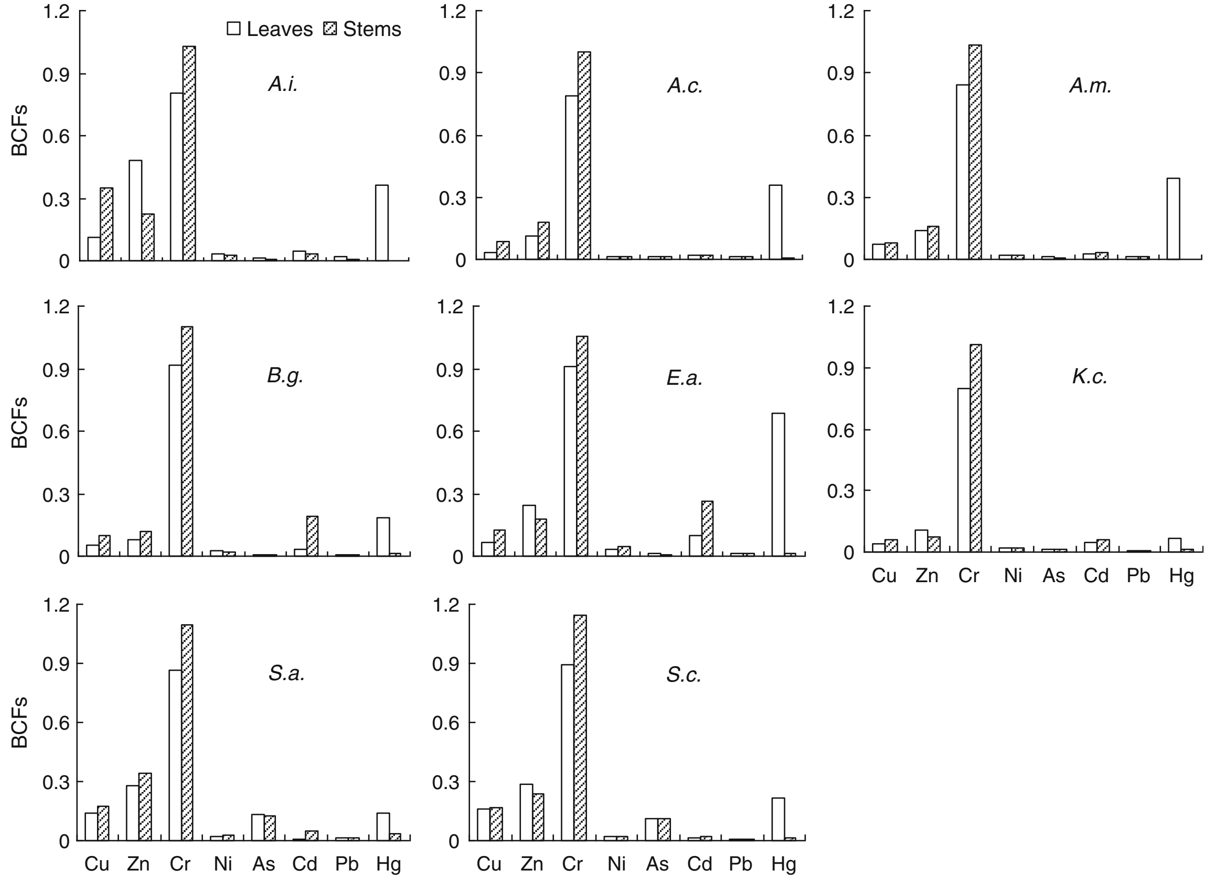

Fig. 2 Heavy metal bioconcentration factors (BCFs) in leaves and stems of mangrove plants in Futian Nature Reserve, Shenzhen Bay. *A.i., A. ilicifolius*; *A.c., A. corniculatum*; *A.m., A. marina*; *B.g., B. gymnorhiza*; *E.a., E. agallocha*; *K.c., K. candel*; *S.a., S. apetala*; *S.c., S. caseolaris*

dominant procedures by which heavy metals are sourced in mangrove plants, heavy metals in leaves and stems were subjected to factor analysis extraction (Agoramoorthy et al. 2008). Three factors extracted using a principal component method described 83.94 % of the total data variability in leaves of eight mangrove plants (Table 3). The dominant Factor 1 accounted for 34.74 %, which described the accumulation of essential element Zn and toxic elements such as As, Pb and Hg. Factor 2 showed significant accumulation of pollution elements Cr, Cd and Ni, which accounted for 28.32 % of total variance. Factor 3 accounted for 20.88 %, showing the loading on essential element Cu, which was lower than Factor 1 and Factor 2. Actually, our finding revealed Zn, As, Pb and Hg significantly accumulated in surrounding soils. Plus, correlation analysis of metal contents in plant tissues was carried out to provide more information about the correlation among metals. Pb concentration in leaves was significantly positively correlated with Hg concentration ($P < 0.05$). Good positive correlation occurred among Zn, As and Pb. Such correlation implied the four metals derived from similar sources and shared similar accumulation mechanisms. Thus, Factor 1 confirmed the contaminated status of the studied soil surroundings. Considering Factor 2, Cr was found remarkably accumulated in mangrove plant tissues. And good correlation was found among Cd, Ni and Cd, implying correlated absorption and transfer procedure. Naturally, such metals occurred in the silicates or basic minerals associated forms, whose mobility was limited, and the environmental fate for them was not correlated with each other significantly. But anthropogenic influence altered their mobility and bioavailability, leading to such good correlation (Asa et al. 2012). Factor 2 confirmed the contaminated

Table 3 Varimax rotated factor matrix for heavy metals found in leaves and stems of mangrove plants in Futian Nature Reserve, Shenzhen Bay

Tissues	Variable	Factor 1	Factor 2	Factor 3
Leaves	Cu	−0.02	−0.13	0.94
	Zn	0.76	0.15	0.56
	Cr	−0.04	0.83	−0.48
	Ni	0.33	0.78	0.38
	As	0.90	0.14	−0.11
	Cd	0.38	0.79	−0.08
	Pb	0.88	0.25	0.18
	Hg	0.59	0.48	−0.21
	Eigenvalues	2.78	2.27	1.67
	Percent variance	34.74 %	28.32 %	20.88 %
Stems	Cu	0.09	−0.06	0.86
	Zn	0.58	0.04	0.79
	Cr	−0.88	0.34	−0.29
	Ni	0.00	0.86	0.27
	As	0.18	−0.42	−0.74
	Cd	0.05	0.99	−0.07
	Pb	0.77	0.05	0.30
	Hg	0.82	0.39	−0.17
	Eigenvalues	2.42	2.18	2.12
	Percent variance	30.20 %	27.21 %	26.48 %

status of the studied mangrove plants. Lastly, Factor 3 represented the plant nutrition status. Similar factor analysis results about heavy metals in stems are also shown in Table 3. The location of the mangrove is an important factor determining the degree of heavy metal pollution. The Futian mangrove is the only mangrove forest located in the center of Shenzhen and has been greatly impacted by significant urban and industrial runoff that contains heavy metals in dissolved or particulate forms. The heavy metal contaminations have contributed to the total metal amounts and significantly affected their cycling in the mangrove ecosystem. However, the lower metal level in aerial parts of mangrove plants in this study may be related to (1) lower transfer of heavy metals from sediments to aboveground parts and (2) lower bioavailability of heavy metals in sediments affected by pH, cation exchange, redox condition and chlorine contents (Du et al. 2002; Nazli and Hashim 2010). Therefore, further study is required to investigate the mobility, bioavailability and toxicity of heavy metals in the Futian mangrove system.

Conclusion

In both the native and exotic Futian mangroves, sediments are contaminated by heavy metals to some extent, with the main contaminants being Zn and As. The heavy metal concentrations in sediments decreased in the order of Zn > As > Cu ≈ Cr > Pb > Ni > Cd ≈ Hg. In leaves and stems, levels of essential elements Cu, Zn and non-essential elements Cr are higher than other metals. The gradient of high heavy metal concentrations (not Cr) in sediments and low levels in leaves and stems clearly indicates that mangrove plants actively avoid the uptake of heavy metals even when sediment concentrations are high. For phytoremediation initiatives, mangrove plants in this study act as phytostabilizers reducing most metals (not Cr) for entry into the food chain. The bioconcentration factors (BCFs) for Cr in stems ranged between 1.00 and 1.15, suggesting its potential use as a temporal Cr contamination indicator in sediments. Anthropogenic sources of heavy metals act as the main factor in affecting the Futian mangrove forest, which deserves great concern.

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References

Agoramoorthy, G., Chen, F. A., & Hsu, M. J. (2008). Threat of heavy metal pollution in halophytic and mangrove plants of Tamil Nadu, India. *Environmental Pollution, 155*, 320–326.

Allen, S. E. (1989). *Chemical analysis of ecological material* (2nd ed., p. 368). Oxford: Blackwell Scientific Publications.

Alongi, D. M., Wattayakorn, G., Boyle, S., Tirendi, F., Payn, C., & Dixon, P. (2004). Influence of roots and climate on mineral and trace element storage and flux in tropical mangrove soils. *Biogeochemistry, 69*, 105–123.

Asa, S. C., Rath, P., Panda, U. C., Parhi, P. K., & Bramha, S. (2012). Application of sequential leaching, risk indices and multivariate statistics to evaluate heavy metal contamination of estuarine sediments: Dhamara Estuary, East Coast of India. *Environmental Monitoring Assessment,*. doi:10.1007/s10661-013-3060-3.

Baker, A. J. M., & Brooks, R. R. (1989). Terrestrial higher plants which hyperaccumulate metallic elements–a review of their distribution, ecology and phytochemistry. *Biorecovery, 1*, 81–126.

Bargagli, R. (1998). *Trace elements in terrestrial plants. An ecophysiological approach to biomonitoring and biorecovery* (p. 324). Berlin: Springer.

Bonanno, G., & Giudice, L. R. (2010). Heavy metal bioaccumulation by the organs of *Phragmites australis* (common) and their potential use as contamination indicators. *Ecological Indicators, 10*, 639–645.

Chaney, R. L. (1989). Toxic element accumulation in soils and crops: Protecting soil fertility and agricultural food chains. In B. Bar-Yosef, N. J. Barrow, & J. Goldshmid (Eds.), *Inorganic contaminants in the Vadose zone* (pp. 140–158). Berlin: Springer.

Chatterjee, M., Massolo, S., Sarkar, S. K., Bhattacharya, A. K., Bhattacharya, B. D., Satpathy, K. K., et al. (2009). An assessment of trace element contamination in intertidal sediment cores of Sunderban mangrove wetland, India for evaluating sediment quality guidelines. *Environmental Monitoring and Assessment, 150*, 307–322.

Cox, R. M., & Hutchinson, T. C. (1981). Multiple and cotolerance to metals in the grass Despitosa Beauv from the sudbury smelting area. *Journal of Plant Nutrition, 3*, 731–741.

Cuong, D. T., Bayen, S., Wurl, O., Subramanian, K., Wong, K. K. S., & Sivasothi, N. (2005). Heavy metal contamination in mangrove habitats of Singapore. *Marine Pollution Bulletin, 50*, 1713–1738.

Dahmani-Muller, H., van Oort, F., Gélie, B., & Balabane, M. (2000). Strategies of heavy metal uptake by three plant species growing near a metal smelter. *Environmental Pollution, 109*, 231–238.

Ding, Z. H., Liu, J. L., Li, L. Q., Lin, H. N., Wu, H., & Hu, Z. Z. (2009). Distribution and speciation of mercury in surficial sediments from main mangrove wetlands in China. *Marine Pollution Bulletin, 58*, 1319–1325.

Ding, Z. H., Tang, Q. H., Liu, C. E., Wang, W. H., Zhuang, M., & Lin, Y. M. (2007). Distribution and ecological effect of mercury in Laogang landfill, Shanghai, China. *Journal of Environment Sciences, 19*, 200–204.

Ding, Z. H., Wu, H., Feng, X. B., Liu, J. L., Liu, Y., Yuan, Y. T., et al. (2010). Distribution of Hg in mangrove trees and its implication for Hg enrichment in the mangrove ecosystem. *Applied Geochemistry, 26*, 205–212.

Du, L. G., Bogaert, N., Tack, F. M. G., Verloo, M. G., & Hendrickx, F. (2002). Heavy metal contents (Cd, Cu, Zn) in spiders (*Pirata piraticus*) living in intertidal sediments of the river Scheldt estuary (Belgium) as affected by substrate characteristics. *Science of the Total Environment, 289*, 71–81.

Essien, J. P., Antai, S. P., & Olajire, A. A. (2009). Distribution, seasonal variations and ecotoxicological significance of heavy metals in sediments of Cross River Estuary mangrove swamp. *Water, Air, and Soil pollution, 197*, 91–105.

Fang, Y., Zheng, W. J., Wan, Y. J., Chen, C. X., & Sheng, H. X. (2008). Effects of chromium (Cr) on the seedling growth of mangrove species Avicennia marina. *Chinese Journal of Ecology, 27*(3), 429–443.

Ferrara, R., Maserti, B. E., & Breder, R. (1991). Mercury in abiotic and biotic compartments of an area affected by a geochemical anomaly (Mt Amiata Italy). *Water, Air, and Soil pollution, 56*, 219–233.

Gao, S., Luo, T. C., Zhang, B. R., Zhang, H. F., Han, Y. W., Zhao, Z. D., et al. (1998). Chemical composition of the continental crust as revealed by studies in East China. *Geochimica et Cosmochimica Acta, 62*, 1959–1975.

Gu, W., Shi, G. X., Zhang, C. Y., Wang, W., Xu, Q. S., Xu, N., et al. (2002). Toxic Effects of Hg^{2+}, Cd^{2+} and Cu^{2+} on photosynthetic systems and protective enzyme systems of *Potamogeton crispus*. *Journal of Plant Physiology and Molecular Biology, 28*(1), 69–74.

Guentzela, J. L., Landing, W. M., Gill, G. A., & Pollman, C. D. (1998). Mercury and major ions in rainfall, through fall, and foliage from the Florida Everglades. *Science of the Total Environment, 213*, 43–51.

Guo, X. Y. (2009). *Effect of Zn-Cd combined stress on the growth and osmotic adjustment substances in Kandelia candel (L.) Druce seedlings*. Xiamen: Xiamen University.

Kabata-Pendias, A., & Pendias, H. (1993). *Biogeochemia pierwiastków śladowych (Biogeochemistry of Trace Element)*. Warszawa: PWN.

Kehrig, H. A., Pinto, F. N., Moreira, I., & Malm, O. (2003). Heavy metal and methylmercury in a tropical coastal estuary and a mangrove in Brazil. *Organic Geochemistry, 34*, 661–669.

Lewis, M., Pryor, R., & Wilking, L. (2011). Fate and effects of anthropogenic chemicals in mangrove ecosystems: A review. *Environmental Pollution, 159*, 2328–2346.

Li, M. S., & Lee, S. Y. (1997). Mangroves of China: A brief review. *Forest Ecology Management, 96*, 241–259.

Li, Y. Y., & Lin, P. (2006). A review on ecological anatomy research of mangrove in China. *Marine Sciences, 30*, 69–73. (in Chinese with English abstract).

Lin, P., Zheng, W. J., & Li, Z. J. (1997). Distribution and accumulation of heavy metals in *Avicennia marina* community in Shenzhen, China. *Journal of Environmental Sciences, 9*, 472–479.

Louis, V. L. S., Rudd, J. W. M., Kelly, C. A., Beaty, K. G., Flett, R. J., & Roulet, N. T. (1996). Production and loss of methylmercury and loss of total mercury from boreal forest catchments containing different types of wetlands. *Environmental Science and Technology, 30*, 2719–2729.

MacFarlane, G. R. (2002). Leaf biochemical parameters in Avicennia marina (Forsk.) Vierh as potential biomarkers of heavy metal stress in estuarine ecosystems. *Marine Pollution Bulletin, 44*, 244–256.

MacFarlane, G. R., Koller, C. E., & Blomberg, S. P. (2007). Accumulation and partitioning of heavy metals in mangroves: A synthesis of field-based studies. *Chemosphere, 69*, 1454–1464.

Mountouris, A., Voutsas, E., & Tassios, D. (2002). Bioconcentration of heavy metals in aquatic environments: The importance of bioavailability. *Marine Pollution Bulletin, 44*, 1136–1141.

Nazli, M. F., & Hashim, N. R. (2010). Heavy metal concentrations in an important mangrove species, *Sonneratia caseolaris* in Peninsular Malaysia. *Environment Asia, 3*, 50–55.

Nobi, E. P., Dilipan, E., Thangaradjou, T., Silvakumar, K., & Kannan, L. (2010). Geochemical and geo-statistical assessment of heavy metal concentration in the sediments of different coastal ecosystems of Andaman Islands, India. *Estuarine, Coastal and Shelf Science, 87*, 253–264.

Ong Che, R. G. (1999). Concentration of 7 heavy metals in sediments and mangrove root samples from Mai Po, Hong Kong. *Marine Pollution Bulletin, 39*, 269–279.

Parvaresh, H., Abedi, Z., Farshchi, P., Karami, M., Khorasani, N., & Karbassi, A. (2011). Bioavailability and concentration of heavy metals in the sediments and leaves of grey mangrove, *Avicennia marina* (Forsk.) Vierh, in Sirik Azini creek, Iran. *Biological Trace Element Research, 143*, 1121–1130.

Qiu, Y. W., Yu, K. F., Zhang, G., & Wang, W. X. (2011). Accumulation and partitioning of seven trace metals in mangroves and sediment cores from three estuarine wetlands of Hainan Island, China. *Journal of Hazardous Materials, 190*, 631–638.

Rönnbäck, P., Troell, M., Kautsky, N., & Primavera, J. H. (1999). Distribution pattern of shrimps and fish among *Avicennia* and *Rhizophora* microhabitats in the Pagbilao mangroves, Philippines. *Estuarine, Coastal and Shelf Science, 48*, 223–234.

Sekomo, C. B., Nkuranga, E., Rousseau, D. P. L., & Lens, P. N. L. (2011). Fate of heavy metals in an urban natural wetland: The Nyabugogo Swamp (Rwanda). *Water, Air, and Soil pollution, 214*, 321–333.

Tam, N. F. Y., & Wong, Y. S. (2000). Spatial variation of heavy metals in surface sediments of Hong Kong mangrove swamps. *Environmental Pollution, 110*, 195–205.

Vane, C. H., Harrison, I., Kim, A. W., Moss-Hayes, V., Vickers, B. P., & Hong, K. (2009). Organic and metal contamination in surface mangrove sediments of South China. *Marine Pollution Bulletin, 58*, 134–144.

Wang, Y. J., & Lin, P. (1998). Annual dynamics of water birds at Futian mangrove zone, Deep Bay, Shenzhen, China. *Journal of Xiamen University, 37*, 121–130. (in Chinese with English abstract).

Wang, Y. J., Ren, Z. G., & Delacy, T. (1999). A preliminary study on the management strategies in Futian mangrove and birds nature reserve, Shenzhen. *Chinese Biodiversity, 7*, 351–354.

Wang, S. H., Yang, Z. M., & Xu, L. L. (2003a). Mechanisms of copper toxicity and resistance of plants. *Ecology and Environment, 3*, 336–341.

Wang, B. S., Zan, Q. J., Zhang, W. Y., & Wang, Y. J. (2003b). Accumulation and cycle of heavy metals in *Sonneratia apetala* and *S. caseolaris* mangrove community at Futian of Shenzhen, China. *Marine Science Bulletin, 5*(1), 59–68.

Xie, H. W., Wen, B., Guo, Y., Shi, Y. Z., & Wu, Y. H. (2010). Community characteristics and distribution of metal elements in mangroves in Futian of Shenzhen, China. *Guihaia, 30*, 64–69. (in Chinese with English abstract).

Yang, Q., Tam, N. F. Y., Wong, Y. S., Luan, T. G., Su, W. S., Lan, C. Y., et al. (2008). Potential use of mangroves as constructed wetland for municipal sewage treatment in Futian, Shenzhen, China. *Marine Pollution Bulletin, 57*, 735–743.

Zan, Q. J., Wang, Y. J., & Wang, B. S. (2002). Accumulation and cycle of heavy metal in *Sonneratia apetala* and *S. caseolaris* mangrove community at Futian of Shenzhen, China. *Environmental Science, 23*, 81–88. (in Chinese with English abstract).

Zan, Q. J., Wang, B. S., Wang, Y. J., & Li, M. J. (2003). Ecological assessment on the introduced *Sonneratia caseolaris* and *Sonneratia apetala* at the mangrove forest of Shenzhen Bay, China. *Acta Botanica Sinica, 45*, 544–551.

Zhang, J., Wang, H., Chen, G., & Li, M. (2001). Transportation, accumulation and circulation of heavy metals in mangrove in Futian, Shenzhen. *Guangzhou Environmental Sciences, 16*, 36–39. (in Chinese with English abstract).

Zhou, Y. W., Peng, Y. S., Li, X. L., & Chen, G. Z. (2011). Accumulation and partitioning of heavy metals in mangrove rhizosphere sediments. *Environment and Earth Science, 64*, 799–807.