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REVIEW ARTICLE

Heavy metal and organic contaminants in mangrove ecosystems of China: a review

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Abstract China's rapid economic growth has been accompanied by increasing environmental pollution. Mangrove ecosystems are now facing greater pollution pressures due to elevated chemical discharges from various land-based sources. Data on the levels of heavy metals and organic pollutants in mangrove compartments (sediments, plants, zoobenthos, and fish) in China over the past 20 years have been summarized to evaluate the current pollution status of the mangrove ecosystem. Overall, the Pearl River and Jiulong River estuaries were severely polluted spots. Concentrations of Cu, Zn, Cd, and Pb in mangrove sediments of Guangdong, Fujian, and Hong Kong were higher than those from Guangxi and Hainan. The pollution status was closely linked to industrialization and urbanization. The highest concentrations of polycyclic aromatic hydrocarbons (PAHs) were found in mangrove sediments from Hong Kong, followed by Fujian and Guangdong. Mangrove plants tend to have low-enriched ability for heavy metals and organic pollutants. Much higher levels of Pb, Cd, and Hg were observed in mollusks.

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Introduction

Mangroves, the intertidal wetlands confined to tropical and subtropical areas, are productive and possess quite a lot of ecological functions (Lin 2001). China occupies a large area of mangroves predominantly distributed in six provinces (Guangdong, Guangxi, Hainan, Fujian, Taiwan, and Zhejiang) and two special administrative regions (Hong Kong and Macao) (Fig. 1). Among them, Guangxi Province has the largest mangrove distribution area (6,170 ha). Hainan Province has the second largest distribution area (4,836 ha) with the most species (Shi 2002). Currently, 34 locally protected reserves have been established in China (Chen et al. 2009a).

Mangroves are special ecosystems with a high level of biodiversity and can provide excellent habitats for organisms (Fan 2002; Wang et al. 2009a). In China, there are overall 37 true and semi-mangrove plant species, belonging to 20 families (Fan 2002). A total of 2,854 biota species including 873 macrobenthos and 258 fish have been recorded in Chinese mangrove ecosystems (He et al. 2007). Some of these organisms (such as gastropods and bivalves) could be regarded as potential bioindicators for environmental pollution (Amin et al. 2009; Yap et al. 2009; Ma et al. 2011; Yap et al. 2011).

Mangroves, one of the most threatened tropical ecosystems, are under increasing pollution pressure from human activities due to rapid industrialization and urbanization of coastal regions. Mangroves can easily accumulate varieties of pollutants mainly derived from rivers or tidal waters due to its unique properties such as high productivity, organic-rich matter scrap, fine grain of wetland soil, and anoxic

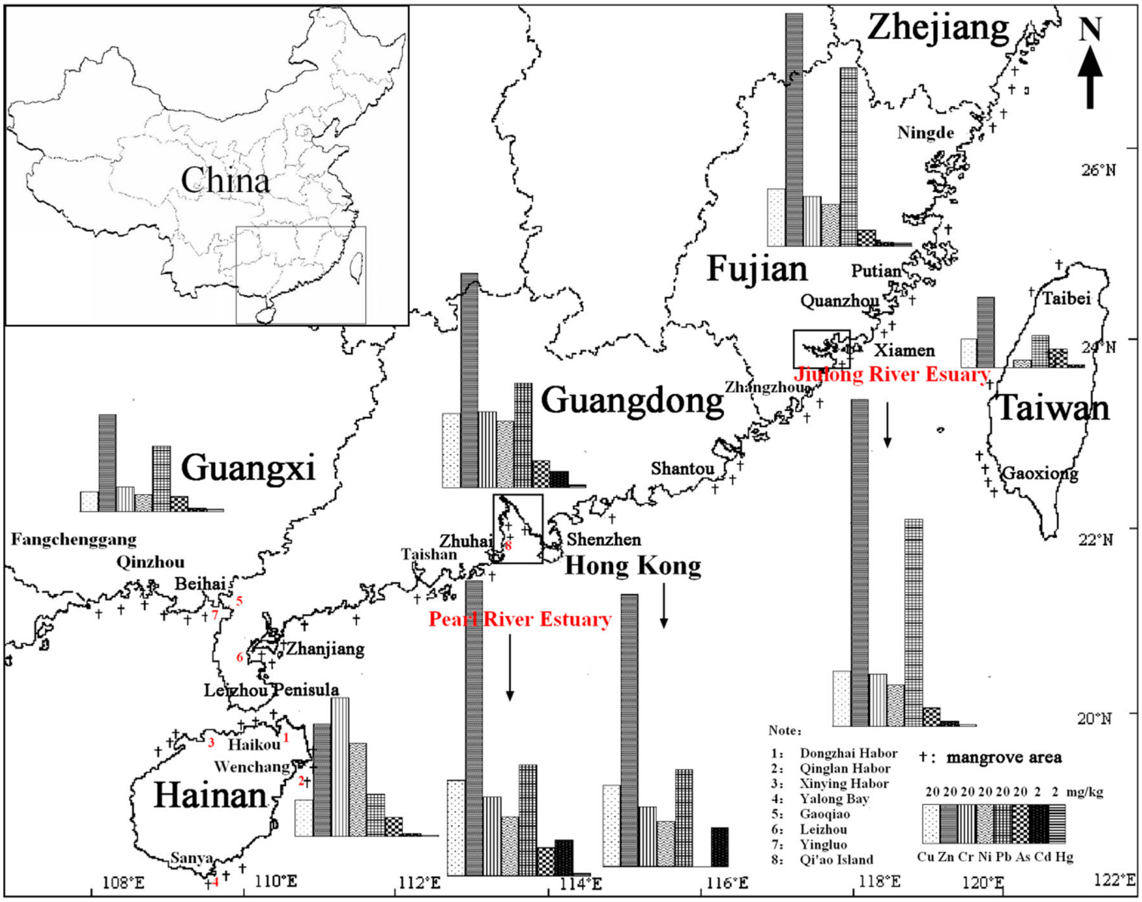

Fig. 1 Heavy metal levels in mangrove sediments of China

environment (Tam 2006; Tang et al. 2008). Pollutants like heavy metals and organic contaminants threatening the mangrove ecosystems are generally toxic and persistent. Heavy metals are nonbiodegradable and may be accumulated via the food chain to hazardous levels (Pan and Wang 2012). To date, heavy metals like Cu, Zn, Mn, Cd, Cr, Pb, and Hg have been frequently detected in mangrove ecosystems. Furthermore, organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and dichlorodiphenyltrichloroethane (DDT), in mangroves have also been of great concern owing to their persistence, bioaccumulation, toxicity, and long-range transport (Fu et al. 2003; Bayen et al. 2005). Both metal and organic contaminants might pose adverse effects to flora and fauna and further affect the ecological functions and stabilization of mangrove ecosystems. It is reported that 29,720 km^2 of offshore areas (including mangrove ecosystems) of China are heavily polluted by heavy metals and organic pollutants with the rapid economic development of coastal regions (NBO 2009). Therefore, understanding better the current pollution status in mangrove ecosystems is important to China's seafood industry and further to public health as well as to a sustainable management of mangrove ecosystems.

The pollution status of mangrove ecosystems in the world could be found in several latest reviews. Lewis et al. (2011) focused mainly on the sediment contamination and bioaccumulation for trace metals. Bayen (2012) described a sketchy status of heavy metal and organic pollutions in mangroves worldwide, without details in China's mangroves. Tam (2006) ever reviewed the pollution studies on mangroves in Hong Kong and Mainland China. However, pollutions in fauna have not been mentioned and quite a lot of comprehensive studies since then have been not included. Additionally, most of the related studies were published in Chinese which may cause some language difficulty to acquire more knowledge on heavy metal and organic pollutions in Chinese mangroves. Therefore, in this review, the occurrence of heavy metal and organic contaminants in mangrove ecosystems of China has been comprehensively evaluated. More than 110 papers published in the past 20 years on contamination of Chinese mangroves have been collected. Pollutants in sediments, mangrove plants, and animals have been involved. This updated review summarized the current contamination status of mangrove systems in China, with discussion on their potential ecological risks, and firstly focused on the pollutions in the fauna from China's mangroves.

Pollutants in sediments

Heavy metals in sediments

Mangrove ecosystems are considered to act as physical and biogeochemical barriers to pollutant transport. Sediment in mangrove ecosystems is a main reservoir of heavy metals for its properties like being anaerobic and reductive and rich in sulfide, organic matter, and iron (Silva et al. 1990; Tam 2006). Heavy metal concentrations in mangrove sediments of Guangdong, Guangxi, Hainan, Fujian, and Hong Kong have been frequently reported. Information about heavy metal pollution in mangrove sediments of Macao, Taiwan, and Zhejiang provinces was scarce (Chiu and Chou 1991; Lai et al. 2010). Related studies mainly focused on metals like Cu, Zn, Mn, Cd, Cr, Ni, Pb, As, and Hg, while few papers involved Co (Zhao et al. 2011).

Heavy metal concentrations in mangrove sediments of China are presented in Table S1 (Supporting Information). Concentrations of Cu, Zn, Mn, Cd, Cr, Ni, Pb, Hg, As, and Co ranged from 0.5 to 93, 9 to 410, 20 to 1,026, nd (not detected) to 5.4, nd to 363, nd to 134, 7 to 180, nd to 0.47, 1.2 to 19, and 6.7 to 15 mg/kg dw (dry weight), respectively. Levels of heavy metals were confined in relatively narrow ranges compared to those in the mangrove sediments worldwide (0.01–4,050, 0.3–2,372, 0.01–87, 0.55–6,240, 0.3–208, 0.08–1,950, <0.01–1.8, 8–40, and 0.6–58 mg/kg dw for Cu, Zn, Cd, Cr, Ni, Pb, Hg, As, and Co, respectively) (Bayen 2012). Background values of heavy metals in China's mangroves have not been studied yet so that values of coastal sediments in China were used as references (Yang 1997; Zhang and Du 2005; Qiao et al. 2009; Gan et al. 2010) (TableS1). A great portion of data was higher than the related background values, showing that mangrove ecosystems in China have been contaminated by heavy metals.

Spatial differences of heavy metal levels were observed in mangrove sediments from China (Fig. 1, Table S1). Overall, concentrations of Cu, Zn, Cd, and Pb in mangrove sediments of Guangdong, Fujian, and Hong Kong were higher than those from Guangxi and Hainan. It may be related to their different extents of industrialization and urbanization. Hong Kong is known as an international metropolis; Guangdong and Fujian are important coastal developed provinces, which are characterized by high density of population and high levels of industrialization. Guangxi and Hainan are newly developing areas in China but are relatively less developed (Qiu et al. 2011). Intense anthropogenic activities in developed areas will lead to more input of metal contaminants. Metal concentrations in mangrove sediments from Taiwan were also in low levels because related data was only from Tamshui River which has been well protected. Mangrove sediments from Hainan had relatively higher concentrations of Cr and Ni and the reason might be ascribed to great storage of these metals but not anthropogenic activities (Vane et al. 2009).

Mangrove sediments in the Pearl River Estuary (including Shenzhen, Zhuhai, and Guangzhou cities of Guangdong and Hong Kong) and Jiulong River Estuary (Zhangzhou and Xiamen cities of Fujian) had higher levels of heavy metals than other regions (Fig. 1). The Pearl River Estuary, exploited since the 1980s, is regarded as a severely polluted estuary area in China. A great deal of Pb, Cd, and Cr, labels of metal pollution in this region, were discharged into the Pearl River every year (Fang 2004). Many studies have been conducted to examine the levels of metal and organic pollutants in sediments from the Pearl River Estuary (Tam and Wong 2000; Fung et al. 2005; Fang 2006; Wei et al. 2006). The pollution in Jiulong River Estuary was related to the development of Xiamen City, a flourishing trade port and an important special economic zone in southeast China (Liu et al. 2006a; Wang et al. 2009b).

In order to explain the potentially ecological risks of heavy metals, prevalent risk assessment criteria of chemicals in sediments from the gulf or estuary reported by Long et a1. (1995) (effects range low, ERL; effects range mean, ERM) were used in this review. Cu, Zn, Cd, and Pb levels in sediments from Guangdong, Fujian, and Hong Kong were above the ERL values but lower than the ERM values, indicating that heavy metals in these regions might pose some negative effects to organisms but of low incidence. Additionally, concentrations of Ni in Leizhou of Guangdong and Sanya of Hainan were higher than the ERM values and deserve great concerns (Table S1). As levels above ERL values were widely found (Table S1) and the reason might be due to the wide use of As-containing pesticides and relatively great background values of As in China (Li et al. 2008; Han et al. 2008). Concentrations of Hg above ERL values were observed in Shenzhen and Zhanjiang of Guangdong, Haikou of Hainan, and Quanzhou and Yantian of Fujian Province. This observation might be related to local economic development, geomorphic and hydrological conditions, and contamination status (Ding et al. 2009).

Total heavy metal levels cannot provide sufficient information about their bioavailability. Heavy metal speciation is available to evaluate their environmental impacts. In a mangrove ecosystem, the available amounts of heavy metals were quite low (Tam and Wong 1995, 1996). Mangrove reforestation could decrease the bioavailability of heavy metals (Zhou et al. 2010a). Extracted Cu, Zn, and Cr accounted for 9–36, 10–17, and 9–36 % of the total levels in mangrove sediments of Zhangjiang River Estuary (Xie et al. 2006). High percentages of Zn, Cr, and Ni were found in the residual fraction (55–62, 64–76, and 65–75 % for Zn, Cr, and Ni, respectively), followed by organic matter/sulfide bound fraction (17–25, 21–33, and 16–25 % for Zn, Cr, and Ni, respectively) in the mangrove sediments of Shantou (Zhou et al. 2011).

Exchangeable and carbonated portions of heavy metals (including Cu, Zn, Ni, and Cr) were less than 10 % compared to the total ones (Chiu and Chou 1991; Tam and Wong 1996). Pb mainly existed in the Fe-Mn oxide fractions while Cd in exchangeable and residual forms (Liu et al. 2006a; Zhou et al. 2011). Acid-volatile sulfide and simultaneously extracted metals (Cu, Cd, Zn, Pb) were detected in sediments from the Jiulong River Estuary and concentrations of simultaneously extracted metals (1.6–5.3 mg/kg) decreased with depth (Liu et al. 2007a). Factors like organic matter, sediment granularity, redox properties, and salinity, and even mariculture activities, could affect the speciation (Bayen 2012; Liang et al. 2012, 2013). Hg in mangrove sediments was highly bioavailable (Ding et al. 2009). Hg mainly exists in volatile form so that it can be easily bioaccumulated (Ding et al. 2009; Yu et al. 2011). However, the residual form of Hg, hardly bioaccumulated, predominated in Shenzhen mangrove sediments (Ding et al. 2010b). Methylmercury (MeHg) was also found in mangrove sediments with concentrations that ranged from 0.24 to 1.56 ng/g dw, which were higher than those in other estuaries of the world (Ding et al. 2010b, c). Methylation of mercury could enhance its lipid solubility and improve bioaccumulation in organisms. Properties like low pH, anaerobic environment, and high contents of sulfide and organic matter will promote the methylation of mercury within sediments to make mangrove wetlands an important pool and source of MeHg (Liu and Ding 2007).

Organic pollutants in sediments

Compared to heavy metal pollution in mangrove sediments, only a few studies have been conducted on organic pollutants in mangrove sediments of China. Limited data mainly focused on PAHs, PCBs, petroleum hydrocarbons, and organochlorine pesticides (OCPs).

PAHs in mangrove sediments

The occurrence of 16 EPA priority PAHs was frequently found in mangrove sediments. PAH levels in mangrove sediments of China ranged from 15 to 11,098 ng/g dw and decreased in the order of Hong Kong (56–11,098 ng/g dw) > Fujian (171–1,074 ng/g dw) > Guangdong (15–726 ng/g dw) > Hainan (31–63 ng/g dw) > Guangxi (24 ng/g dw) (Table 1). Higher concentrations of PAHs were found in the mangrove sediments of Hong Kong and the reason might be attributed to the intense anthropogenic activities such as prosperous shipping, incomplete combustion of fuels from vehicles, and sewage discharges. Point sources may exist in Hong Kong, and PAH concentrations in the sediments from Ho Chung, Mai Po, and Ma Wan were 1–2 magnitude orders higher than those from other sites. PAH level in Yi O mangrove sediments was up to 2,135 ng/g dw due to an accidental oil spill (Ke et al. 2002). Values in mangrove sediments of China (24–11,098 ng/g dw) were far below ERM (44,792 ng/g dw) (Table 1), and mean concentrations of PAHs in Hong Kong were also lower than ERL, indicating that PAHs may pose little risk to biota in mangrove ecosystems (Tam et al. 2001). Therefore, PAHs might not be a major threat to Chinese mangrove ecosystems.

For PAH composition, high molecular weight PAHs dominated in most mangrove sediments. In Yi O, Ma Wan (in Hong Kong), Jiulong River Estuary, and Deep Bay, high percentages of high molecular weight PAHs (four–six rings) were found in the sediments (Ke et al. 2002; Zhang et al. 2004; Tian et al. 2008b; Li et al. 2009), while PAHs in sediments of Hong Kong mangrove were dominated by two rings (naphthalene) and three rings (phenanthrene) (Tam et al. 2001). PAHs in sediments from Shantou mangroves were dominated by phenanthrene (three rings), fluoranthene (four rings), pyrene (four rings), and benzo(*k*)fluoranthene (five rings) (Cao et al. 2009b). PAH contamination might mainly come from petrogenic sources (Tian et al. 2008b), pyrolytic sources (Tam et al. 2001), or a combination of both (Ke et al. 2002) through source-diagnostic ratios. PAHs in sediments of Ho Chung were more dominated by pyrolytic input while petrogenic contamination in Tolo (Tam et al. 2001). Furthermore, principal component analyses showed that the main PAH sources were biomass/coal combustion and vehicular emission in Shantou and Deep Bay (Cao et al. 2011). As for the PAH compositions, many factors such as physiochemical properties of the sediments, contents of organic carbon, and black carbon could affect PAH concentrations (Cao et al. 2009c, d).

PCBs in mangrove sediments

PCBs were detected in mangrove sediments from China with concentrations that ranged from <0.1 to 47 ng/g dw (Table 1). In general, PCB concentrations in sediments from Hong Kong, Shenzhen, and Zhuhai were slightly higher than those from other locations, showing that mangrove sediments in the Pearl River Estuary were heavily polluted by PCBs (Table 1). This result was similar to previous studies on PCBs in sediments of the Pearl River Estuary (Hong et al. 1995; Hong et al. 1999; Wu et al. 1999; Yang et al. 2009). The relatively high PCB levels in sediments from the Pearl River Estuary could be linked to high density of electronic/electrical industries and electronic waste (e-waste) recycling activities (Sun et al. 2012). Higher levels of PCBs were also reported in air, fish, and birds at the e-waste recycling sites from the Pearl River Estuary (Chen et al. 2009a; Luo et al. 2009; Zhang et al. 2010). It has been estimated that 145 million electronic devices (such as television, electric fans, and computers) were disposed in Guangdong in 2002 (Martin et al. 2004). Intensive e-waste recycling activities may accelerate the release of PCBs into the environment.

Table 1 Concentrations of PAHs and PCBs (ng/g dw) in mangrove sediments of China

Pollutants	Areas	Sampling stations	Mean/range	References
PAHs	Hong Kong	Mai Po	178–4,842	Zheng et al. (2000); Tam et al. (2001); Tam et al. (2002); Zhao et al. (2012b)
		Ma Wan	791–5,041	Tam et al. (2002); Li et al. (2009); Ke et al. (2005)
		Yio	73–2,135	Ke et al. (2002); Ke et al. (2005)
		Ho Chung	1,162–11,098	Tam et al. (2001); Yu et al. (2005)
		Sai Keng	839–2,140	Tam et al. (2001); Tam et al. (2002)
		Sheung Pak Nai	59–241	Tam et al. (2002); Ke et al. (2005)
		Tolo	1,041	Tam et al. (2001)
		Ting Kok	56–172	Ke et al. (2005)
	Guangdong	Shenzhen	237–726	Vane et al. (2009); Zhang et al. (2004)
		Shantou	15–238	Cao et al. (2009b); Wu et al. (2009)
		Zhanjiang	31–242	Tang et al. (2008); Vane et al. (2009)
	Fujian	Xiamen	171–223	Tian et al. (2008b); Vane et al. (2009)
		Jiulong River Estuary	193–1,074	Zhang et al. (2003); Lu et al. (2005, 2007); Tian et al. (2008a)
	Guangxi	Beihai	24	Vane et al. (2009)
	Hainan	Haikou	31–63	Vane et al. (2009)
		Wenchang	75	Vane et al. (2009)
	ERL		4,022	Long et al. (1995)
	ERM		44,792	Long et al. (1995)
PCBs	Hong Kong	Several sites	<0.1–25	Tam and Yao (2002), Zheng et al. (2000)
	Guangdong	Zhuhai	14–41	Zhao et al. (2012a)
		Shenzhen	2.9–47	Vane et al. (2009); Zhao et al. (2012a)
		Shantou	3.0–25	Zhao et al. (2012a)
		Zhanjiang	3.8	Vane et al. (2009)
	Hainan	Haikou	4.4–6.0	Vane et al. (2009)
		Wenchang	4.5	Vane et al. (2009)
	Fujian	Xiamen	4.4	Vane et al. (2009)
	Guangxi	Beihai	3.4	Vane et al. (2009)
	ERL		23	Long et al. (1995)
	ERM		180	Long et al. (1995)

Other organic pollutants in sediments

Information on other organic pollutants in mangrove sediments is limited. Total petroleum hydrocarbons (TPHs) in sediments were in the range of 32–570 mg/kg dw and a higher level of TPHs was observed in the Pearl River Estuary (Zheng et al. 2000; Tam et al. 2005; Vane et al. 2009). Sources of TPHs in the Pearl River Estuary were mainly derived from vehicle exhausts and incomplete combustion (Vane et al. 2009). The fuel oil contamination in a mangrove swamp in Hong Kong was reported with mean TPH levels in the root zone sediments up to 1,000 mg/kg dw (Tam et al. 2005). HCHs, heptachlor, aldrine, heptachlor epoxide, γ-chlordane, α-chlordane, *p,p*′-DDE, *p,p*′-DDT, and endrine were detected in surface sediments of mudflat and mangroves at Mai Po, Hong Kong with concentrations of 9.7–28.5, <0.01–9.1, 1.3–9.2, 1.1–11, 0.9–6.8, <0.01, 1.9–10, 1.5–6.4, <0.01–2.8 ng/g dw, respectively (Zheng et al. 2000). Tang et al. (2008) reported that the average concentrations of DDTs and HCHs were 28 and 0.07 ng/g dw in Leizhou Peninsula. Ten pesticides were detected in the mangrove sediments of Daguansha, Guangxi with concentrations that ranged from 0.01 to 6.9 ng/g dw (Zhou et al. 2010b). Among these pesticides, fenobucarb, fenpropathrin, and kresoxim-methyl were detected in 77, 100, and 100 % of the samples. Polybrominated diphenyl ethers (PBDEs), used widely as flame retardants, have been detected in Hong Kong mangroves with the concentrations of BDE 209 and $\sum$PBDEs (seven congeners except BDE 209) in the ranges of 1.53–75.9 and 0.57–14.4 ng/g dw, respectively (Zhu et al. 2014). Their results were much higher than those reported in mangrove sediments of Singapore, India, and Senegal, indicating severe pollution of PBDEs in this area (Bayen et al. 2005; Binelli et al.

2007; Bodin et al. 2011). An escalating trend in the concentrations of PBDEs in sediment cores suggested the continuous inputs of PBDEs.

Pollutants in mangrove plants

Mangrove plants are a crucial member in the ecosystem and they appear to be highly tolerant to pollutants by different adaptive strategies. They likely perform as excluder species for nonessential metals and regulators for essential metals which make them excellent candidates for phytostabilization of heavy metals in intertidal areas (Tam et al. 1995; MacFarlane et al. 2007; Liu et al. 2009; Li et al. 2010; Zhou et al. 2010a; Zhou et al. 2011). Mangrove plants are also proven to be able to endure and adapt to definite concentrations of POPs through physiological and biochemical mechanisms (Liu et al. 2007b; Ke et al. 2011). Additionally, many microorganisms isolated from mangrove sediments turned out to be efficient consumers of organic pollutants and, thus, may decrease the residue levels of organic pollutants in mangrove environments (Guo et al. 2005; Xu et al. 2005a, b; Yu et al. 2005; Xu et al. 2007; Zhou et al. 2008). Therefore, mangrove wetlands are being used as potential waste treatment facilities (Tam 2006). Other than many laboratory experiments which focused on the physiological and molecular features of individual species, a large amount of field work has been conducted to monitor pollution in mangrove plants (Zheng et al. 1996a, b; Zheng and Lin 1996a, b; Lian et al. 1999; Ding et al. 2011). Heavy metals have been detected in various tissues such as the root, leaf, branch, fruit, stalk, and propagule of mangrove plants from different locations.

Metals in mangrove plants

Currently, at least 15 mangrove species including *Sonneratia caseolaris*, *Sonneratia hainanensis*, *Sonneratia ovata*, *Sonneratia apetala*, *Kandelia candel*, *Bruguiera gymnorrhiza*, *Bruguiera sexangula*, *Aegicera corniculatum*, *Aegicera marina*, *Aegicera ilicifolius*, *Ceriops tagal*, *Rhizophora stylosa*, *Rhizophora apiculata*, *Excoecaria agallocha*, and *Lumnitzera apiculatal* were served as study materials. Among these species, *K. candel* has been studied most. Cu, Zn, Pb, and Cd were the most studied elements and metals like As and Hg were seldom reported. Concentrations of Cu, Pb, Zn, Cd, Cr, Ni, Mn, Hg, and As in plants ranged from <1 to 359, nd to 113, 0.8 to 340, nd to 1.8, 0.2 to 37.7, 0.2 to 50, 4 to 2,160, 0.02 to 4.3, and nd to 0.9 mg/kg dw, respectively. Metal concentrations in mangrove species especially *K. candel* were over a broad range (Cu, Pb, Zn, Cd, Cr, Ni, and Mn concentrations ranged from 1.4 to 359, nd to 113, 6.8 to 340, nd to 1.8, nd to 36.8, 0.4 to 50, and 27 to 2,160 mg/kg dw, respectively) (Fig. 2). Accumulation and distribution of metal elements in mangrove plants might be dependent on the levels of metal elements in forest sediments (Xie et al. 2010). Concentrations of heavy metals showed variations in different species and tissue. For example, *K. candel* accumulated more Ni; *A. marina* tended to accumulate higher Pb and *A. corniculatum* was apt to accumulate greater Cr (Xie et al. 2010). Accumulating abilities of Cu, Pb, Zn, Ni, and Cr in three mangrove plant species decreased in the following sequence: *S. caseolaris* > *S. apetala* > *K. candel* (Zan et al. 2002). Enrichment abilities of Cu, Pb, and Zn in five mangrove plant species decreased in the order of *C. tagal* > *B. sexangula* > *K. candel* > *A. corniculatum* > *B. gymnorrhiza* (Li et al. 2013). Concentrations of Cu, Pb, Zn, and Cr in fine roots were much higher than those in branches, stalks, and leaves (Zan et al. 2002; Wang et al. 2013). However, in other *S. apetala* communities, Zn was most accumulated in the leaves and the highest Cu concentration was found in perennial branches (Han et al. 2004). In mangrove tissues of nine species from Hainan, Zn and Cu were generally enriched in fruit; Hg in leaf; Pb, Cd, and Cr in branch; and As in root (Qiu and Yu 2011). Concentrations of Hg in different *K. candel* tissues decreased as follows: leaf > bark > root > xylem (Liang et al. 2011). It is suggested that mangrove plants could accumulate nonessential metals in perennial tissues to reduce the export of these metals through leaf litter transport (Zhou et al. 2011). Ding et al. (2011) found that total Hg and MeHg concentrations (462–3,120 and 0.22–1.76 ng/g dw) in mangrove plants were much higher than those in terrestrial plants, and enrichment ability for total Hg and MeHg in mangrove plants varied with species. Mature leaves tended to accumulate more total Hg, while juvenile ones seemed to uptake more MeHg (Ding et al. 2010a).

Biosediment accumulation factors (BSAFs) are defined as heavy metal concentrations in tissues divided by the concentrations in sediments. The BSAFs for each element might vary, but most values were less than 1 (Zheng et al. 1996a; Wang et al. 1997; Ong Che 1999; Zan et al. 2002; Wang 2011). The BSAFs decreased in the order of Hg (0.43)>Cu (0.27)>Cd (0.22)>Zn (0.17)>Pb (0.07)>Cr (0.06)>As (0.02) for Hainan mangroves (Qiu and Yu 2011); Zn (0.15–0.20)>Cu (0.06–0.16)>Pb (0.05–0.07)>Ni (0.03–0.04)>Cr (0.02–0.03) for Shenzhen mangroves (Zan et al. 2002); and Zn (0.2–1.3)>Cd (0.4–1.2)>Cu (0.07–0.57)>Mn (0.02–0.21)>Pb (<0.01) for propagules of ten mangrove species (Lian et al. 1999). On the whole, mangrove plants tend to accumulate limited heavy metals. Metal concentrations in wetlands may not be high enough to harm the plants.

Organic pollutions in mangrove plants

A few field studies involved organic pollutants in mangrove plants. Organic pollutants in sediments may hardly do harm

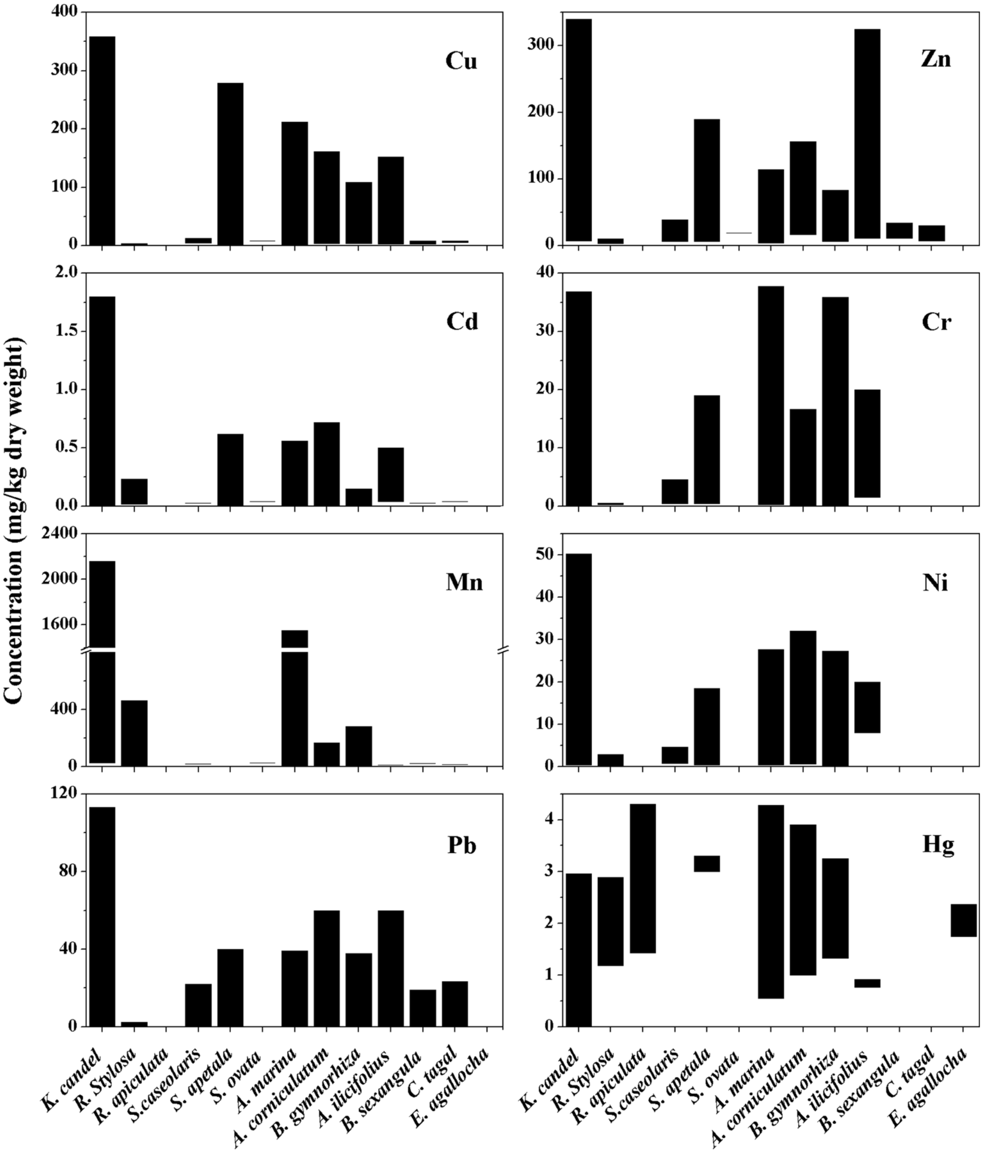

Fig. 2 Concentration ranges of heavy metals in mangrove plants of China

mangrove plants for the levels of these pollutants might be much lower than the toxic concentrations observed in the laboratories. It was reported that the seedlings of *A. corniculatum* grew normally at PCB concentration of 2,700 ng/g dw which was at least one magnitude higher than the field data (Liu et al. 2006b). Higher OCP levels (3,313–4,083 ng/g dw) in *K. candel* were found in hypocotyls and much lower concentrations (49–97 ng/g dw) existed in the stem. Monthly changes of OCP content in the leaves of mangrove plants were also observed and the highest concentration of OCPs in *A. corniculatum* was in September (619 ng/g dw) and the lowest in April (135 ng/g dw), while for *K. candel*, the highest values were in February (490 ng/g dw) and the lowest in December (124 ng/g dw) (Lin et al. 1994). Total PAH concentrations in the roots of three mangrove species (*K. candel*, *A. marina*, and *B. gymnorrhiza*) ranged from 30.8 to 62.7 ng/g dw (Lu et al. 2005).

Pollutants in zoobenthos and fish

Metals in benthos and fish

Heavy metals were determined in 45 species including worms, mollusks, crustaceans, and fish from Yingluo Bay in Guangxi, Ting Kok in Hong Kong, Dongzhaigang in Hainan, and Shenzhen in Guangdong (Tables 2 and S2). Wide ranges of metals were observed in different species. In Yingluo Bay, Guangxi, mollusks accumulated more Zn and Cd, while crustacean had more Cu. The highest levels of Cu, Zn, Cd, and Pb were observed in *Cyclina sinensis*, *Phascolosoma esculenta*, and *Ostrea crenulifera*, respectively (He et al. 1996). Lai and Qiu (1998) found that Hg levels ranged from 3.0 to 5,310 ng/g dw and the highest concentration was detected in *Solen grandis*. For Ting Kok, Hong Kong, Chen et al. (2003) investigated concentrations of heavy metals (Cu, Pb, Zn, and Ni) in

Table 2 Concentrations (mg/kg dw) of heavy metals in mangrove fauna of China

Location	Biota	Cu	Pb	Zn	Cd	Hg	Ni	As	References
Guangxi	Sipunculida	nd–24	1.2–34	356–122	nd–1.8	0.2–3.5			He et al. (1996), Lai and Qiu (1998)
	Gastropoda	5.9–136	2.8–10	80–302	1.2–5.2	<0.01–2			
	Bivalve	nd–346	nd–31	28–615	nd–35.2	<0.01–5.3			
	Brachipoda	nd–13	1.8–1.9	102–185	3.4–3.5	0.15–0.19			
	Crustacean	2.6–169	0.9–33	75–163	nd–5.5	0.08–1.7			
	Fish	5.2	2.9	70.7	0.5	0.14			
Hong Kong	Bivalve	12–378	10–20	76–3,913			8–16		Chen et al. (2003)
Guangdong[a]	Crustacean				1.0–1.2	0.03–0.04		0.05–0.1	Liu et al. (2008)
Hainan[a]	Fish					<0.01–0.2			Zhang et al. (2011)
Residue limit[a]	Crustacean	50	0.5		0.5	0.5		0.5	NY 5073-2006
Residue limit[a]	Mollusk	50	1		1	0.5		0.5	
Residue limit[a]	Fish	50	0.5		0.1	0.5		0.1	

nd not detected

[a] Wet weight

bivalves and found that Zn and Cu levels in bivalves were much greater than Pb and Ni. *Saccostrea cucullata* had the highest contents of Zn and Cu among the studied five bivalves with concentrations of 3,913 and 378 mg/kg dw. Zhang et al. (2011) analyzed Hg concentrations in 14 fish species collected from Dongzhaigang mangrove forest, Hainan. The concentrations in fish muscles ranged from 35 to 155 ng/g ww (wet weight) with an average of 68 ng/g ww. Hg concentrations in fish were related to their feeding and living habits. Hg, Pb, Cd, and As were detected in mud crab (*Scylla serrata*) from mangrove plant-culturing wetlands in Shenzhen, and low levels of Hg (0.03–0.04 mg/kg ww) and As (0.05–0.1 mg/kg ww) and relatively high levels of Cd (1–1.2 mg/kg ww) were observed (Liu et al. 2008).

Residue limits of toxic substances in nuisanceless foods and aquatic products (NY 5073-2006) issued by the Ministry of Agriculture, China were utilized for evaluating the consumption safety of fauna and fish from mangroves although some of these species might be unsuitable for consumption. Hg was not a concern when considering the consumption safety of fish from Hainan for all the values were far below the residue limit (Zhang et al. 2011). Contamination of Pb, Cd, and Hg in macrobenthos especially mollusks should be paid more attention because these metals in some biota might be higher than the maximum residue limits, assuming that the water content ratios were 85 % in fauna, and its metal concentrations were expressed on a dry weight basis. Different degrees of over-standard ratio were also reported (He et al. 1996; Lai and Qiu 1998; Chen et al. 2003; Liu et al. 2008).

Zoobenthos are frequently used as bioindicators to measure levels of heavy metals for their being relatively sedentary, easy to identify, abundant, long-lived, available for sampling all year round, and getting a wide distribution area (Rainbow 1995). A gastropod species, *Sermyla tornatella*, one of the dominant species which has a wide distribution in Mai Po, Hong Kong was used in a field toxicity experiment to investigate its probability as a bioindicator of Mai Po Marshes (Liang 2007). Results showed that metal bioaccumulation seemed to have no effect on the growth and mortality of *S. tornatella*, whereas food quality and environmental factors were more relevant to its survival. An amphibian species, *Rana cancrivora*, can be acted as an indicator species whose activity of superoxide dismutase, catalase, and acetylcholine esterase was higher in the samples from the core mangrove area than those from the pier of the National Dongzhai Habor Mangrove Reserve, indicating the lower quality of pier habitat which has to endure more human intervention and traveling (Li et al. 2012a).

Organic pollutants in zoobenthos and fish

Only a few studies are related to organic pollutants in mangrove fauna. Organic pollutants like PAHs, OCPs, and antibiotics were detected in more than 20 species. The range of PAHs in the zoobenthos and fish was 5.5–854 ng/g dw and the highest concentrations were found in *Sarotherodon mossambicus* at Mai Po Marshes Nature Reserve, Hong Kong (Table 3). Levels in fish from Hong Kong seemed to be much higher although some factors like species, tissue, size, age, and sampling season could affect the accumulation of PAHs in fauna. Compositions of PAHs varied among species. For example, Cai et al. (2005) observed that the main PAH compositions of *Neritina violacea* and *Trypauchen vagina* were tetra- and penta-aromatics, while *Periophthalmus cantonensis*, *Littoraria melanostoma*, *Cerithidea djadjariensis*, and *P. esculenta* were predominated by bi-aromatics. In aquatic products, *Tilapia mossambica*, *Mugil cephalus*, and *Concha ostreae* from mangrove

Table 3 PAH concentrations (ng/g dw) in the fauna collected from mangroves of China

Biota	Species	Sampling sites	PAHs	References
Fish	*Sarotherodon mossambicus*	Hong Kong	184–854	Liang et al. (2007)
	Tilapia mossambica	Shenzhen	12–14	Chen et al. (2012)
	Mugil cephalus	Shenzhen	26–35	Chen et al. (2012)
	Trypauchen vagina	Jiulong River Estuary	5.5	Cai et al. (2005)
Bivalve	*Concha ostreae*	Shenzhen	90–99	Chen et al. (2012)
Gastropoda	*Neritina violacea*	Jiulong River Estuary	110	Cai et al. (2005)
	Littoraria melanostoma	Jiulong River Estuary	61	Cai et al. (2005)
	Periophthalmus cantonensis	Jiulong River Estuary	41	Cai et al. (2005)
	Cerithidea djadjariensis	Jiulong River Estuary	32	Cai et al. (2005)
Sipunculida	*Phascolosoma esculenta*	Jiulong River Estuary	59	Cai et al. (2005)

planting-aquaculture ecosystem in Shenzhen were characterized by three rings (Chen et al. 2012).

OCPs were also detected in several species from different locations. OCPs were found in some species including *Ostrea* sp., *P. cantonensis*, opossum shrimp, *Orithyia sinica*, and *M. cephalus* collected from the mangrove area of Jiulong River Estuary, Fujian with levels of 25–1,610 ng/g dw. The products were considered to be safe for consumption (Lin and Huang 1994). Distributions and contents of pesticides and antibiotics in sediments and benthos (*Onchidium verruculatum*, *Mictyris longicarpus*, and *Anomalocordia lexuosa*) collected from Daguansha mangrove in Guangxi were investigated, where fish farming sewage was heavily discharged (Zhou et al. 2010b). Four pesticides and three antibiotics were detected in the benthos. The results showed that mangrove sediments were easily polluted by aquaculture drainages than benthos.

TPHs were detected in oysters from several ponds of the plantation-aquaculture coupling ecosystems in the Pearl River Estuary with concentrations ranging 11–29 mg/kg dw (Li et al. 2012b). TPHs were also found in crabs and conchs from Shoutou mangroves and they might come from petrogenic, biogenic, and plant wax (Cao et al. 2009a). Triphenyltin, tributyltin, and dibutyltin were detected in marine animals from intertidal areas at Shekou Harbor and Shenzhen Bay with levels of 127–349, 6.3–381, and 2.7–100 ng/g ww, respectively. Marine animals from mangrove areas had lower levels of organotin contaminant than those from the harbor (Deng et al. 2009). Organotin compounds, widely used in antifouling of ships, might be released into marine ecosystems through a variety of maritime activities.

Conclusions and perspectives

The occurrence of heavy metal and organic contaminants in mangrove ecosystems of China was comprehensively reviewed. Generally, mangrove ecosystems in the Pearl River and Jiulong River estuaries were severely contaminated by heavy metals and organic pollutants. Mangrove sediments from Guangdong, Fujian, and Hong Kong had higher levels of Cu, Zn, Cd, and Pb compared to those from Guangxi and Hainan. PAH levels in mangrove sediments of China decreased in the order of Hong Kong > Fujian > Guangdong > Hainan > Guangxi. Much higher concentrations of PCBs were found in mangrove sediments from Hong Kong, Shenzhen, and Zhuhai. The BSAFs for heavy metals (except Mn) of mangrove plants were less than 1. Mollusks had higher levels of Pb, Cd, and Hg than other biota groups.

In the future, much effort on mangrove pollution should be paid on the following aspects: (1) Sediment cores are needed to have a better understanding of the vertical/historical record of various contaminants, although it is of difficulty to get over the muddy, hard-to-transit, and rooty conditions of the mangrove forests; (2) organic pollutants except traditional POPs should be given more attention since very limited available information about the organic pollution status in China's mangroves has been known. Some emerging pollutants like PBDEs and the compounds which escaped from the conventional list should necessarily be monitored; organometalic compounds like MeHg and organotin which are quite toxic deserve more investigations. (3) Advanced detection techniques should be applied to measure these trace contaminants; (4) studies on the transport and transformation of pollutants through the interface of water-sediment-plant could be helpful for a systematical understanding of the cycling of pollutants in a mangrove ecosystem; (5) pollutant concentrations in predators (birds, animals adjacent to mangroves, even fishermen) in high tropical levels could be involved. More work should be conducted to monitor the metal pollution in mangrove macrobenthos and some potential bioindicators should be explored; and (6) criteria evaluating ecological risks suitable for mangrove ecosystems or coastal areas of China should be established.

In order to protect mangrove ecosystems, many stringent measures should be taken to reduce the discharge of pollutants from various anthropogenic sources. Risk assessment of a contaminated ecosystem, including fauna, should be based on the integration of both heavy metals and organic pollutants, neither on single heavy metal or organic pollutants. Furthermore, it is urgent to increase public awareness of mangrove protection to support sustainable resource management and restoration activities.

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