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Heavy Metal Pollution in *Avicennia marina* Mangrove Systems on the Red Sea Coast of Saudi Arabia

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Abstract. The dynamics of eight heavy metals including Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Cadmium (Cd) and Lead (Pb) were assessed in two mangrove system on the Red Sea coast including an industrially exposed site at Yanbu city and a minimal exposed site at Shuaiba. Heavy metal concentrations were measured in mangrove tree components, in sediment and in fallen litter *via* nitric perchloric acid digestion. It was found that mangrove sediments were the main stocks for heavy metals followed by mangrove woods, a minimal amount (< 3.5%) of heavy metals was returned back to the sediment *via* litterfall out of which, less that 1% was removed away from the mangrove system via tidal activities. In addition, heavy metal concentrations were generally found to be below contamination limits suggesting that these mangrove systems are relatively clean from heavy metal pollution. However, concentrations were always higher in Yanbu (the exposed site) than in Shuaiba (the less exposed site) suggesting the need for future monitoring and assessment.

Keywords: Avicennia marina; Red Sea coast; heavy metals bioaccumulation; coastal pollution; sediment pollution.

Introduction

Coastal areas are largely affected by pollution from different anthropogenic sources including oil spilling, dredging, urban discharges, agricultural and industrial wastewater. Due to their toxicity, bioaccumulation capacity and persistence, heavy metals represent a significant and serious pollution source that is associated with anthropogenic activities in coastal environments (Harbison, 1986; Clark *et al.,* 1998 and Tam and Wong, 2000). Mangrove systems occupy the intertidal areas of the coasts and thus, are extremely exposed to heavy metal pollutants from various sources. In addition, the anaerobic sulphide-rich sediment with its high metal binding capability can trap metals in mangrove sediments, increasing concentration and therefore increasing accumulation in sediment and plant tissues (Mackey and Mackay, 1996 and MacFarlane *et al.,* 2003).

Mangrove trees are reported to tolerate high levels of heavy metals (MacFarlane, 2007) with *Avicennia* species exhibiting greater tolerance and accumulative properties to numerous metals than other mangrove species (MacFarlane and Burchett, 2002). Moreover, mangrove trees that grow on sediments with high levels of heavy metals exclude and regulate uptake of metals at the root level depending on their importance (*i.e.* essential or non-essential metals) (Lacerda *et al.,* 1993 and MacFarlane and Burchett, 2002). The cycling and export of heavy metals is a function of metal concentration in litterfall produced, decomposition, residence time and tidal activities (Silva *et al.,* 2006). High concentrations of heavy metals in the plant can reach toxic levels in which metals with high concentrations are excluded from the plant via translocation to senescent leaves that are about to fall; litterfall containing high levels of excluded heavy metals can in turn release a significant amount of heavy metals through decomposition into the sediment, and when accompanied by high tidal activities, export metals to adjacent systems (Silva *et al.,* 2006).

The overall objective of this study was to assess the current environmental condition and heavy metal pollution of mangrove systems in two locations on the Red Sea coast. This was achieved through assessing the following:

1. Heavy metal concentrations in mangrove trees and sediment.

2. Heavy metal input, release and possible export from the mangrove systems through estimates of litterfall production, decomposition, residence time and tidal activities.

Methodology

Sampling Procedure

Two mangrove sites on the Red Sea coast were selected for the present study, a northern site located in the industrial city of Yanbu (24^o 02' 65" N and 38^o 09' 46"E) and a southern site in Shuaiba region (20^o46' 2"N and 39^o 30' 21"E). At Shuaiba site, a trend in tree density, size and height was found; thus, four transects were set in north-south orientation perpendicular to the variation. Three permanent plots (50×50 m) were set at a distance of 100 m along each transect with a total of 12 plots per site. In Yanbu, trees were homogenous in growth and density and therefore, 12 plots (50×50 m) were randomly located on the site.

For all tree components (*i.e.* leaves, branches, stems, aerial roots and fine roots), 3 samples per component per site were used for heavy metal analysis. Green leaves, branches, and stem were randomly sampled from trees in different plots. Aerial roots were sampled by placing a 1 m^2 quadrat at 1, 2 and 3 metres away from trees and roots within the quadrats were sampled (3 samples per distance). Fine roots were sampled at depths reaching 50 cm using a 1.9 cm radius corer. Random coring was taken at 1 m and 2.5 m distance away from mangrove trees.

The input, release and possible export of heavy metals in the mangrove system were assessed through estimating leaf litterfall production, standing crop litter and litter decomposition. Annual litterfall and standing crop production was estimated monthly over a period of 2 years (from 2007 to 2009) using litter trap and ground plot techniques respectively. Annual estimate of litterfall and standing crop in each site were pooled and three subsamples were taken for heavy metal determination. Litter decomposition was estimated by placing 30 g of senescent leaves into 25 cm^2 mesh bags and 3 decomposition bags were sampled at nine sampling intervals on days 1, 2, 4, 8, 16, 32, 64, and 128. The weight loss of the decomposing litter was expressed using the single exponential model:

$$y = W_1 \, e^{-k_1 t}$$

where y is the dry mass remaining at time t (days) and k is the decay constant.

To estimate the heavy metal input through leaf litterfall, the mean concentration of metals in leaf litter were multiplied by the mean leaf litterfall rate (kg ha^{-1} y^{-1}). Metal concentrations in decomposing litter were assessed by taking subsamples of decomposed litter at each sampling time and analysed for metal concentrations with a total of 21 samples per site for the whole decomposition study.

Plant metal uptake was assessed via three measurements of root concentration factor (RCF) assessing the metal concentrations in roots relative to sediment metal concentration, leaf concentration factor (LCF) assessing the metal concentration in leaves relative to the sediment metal concentration and finally metal translocation factor (TF) assessing the transport of root metals to leaves (MacFarlane *et al.,* 2007). The export of heavy metal from the mangrove system is a function of the tidal ranges, litter residence time and its metal concentration. Tidal information was obtained from the Saudi Aramco Tidal Tables (Saudi Aramco Tidal Tables, 2007, 2008 and 2009) for Shuaiba and Yanbu; the residence time of litter on the forest floor surface was calculated using the equation:

$$\tau = Xss / L$$

where τ is residence time, Xss is the annual rate of litter standing crop and L is the annual rate of litterfall input.

The turnover of the heavy metals in each site was estimated using a ratio of the metal in the perennial biomass to the annual input of litter through litterfall (Silva *et al.,* 2007).

Sediment samples were taken from plots using random coring with a total of 15 samples per site. Sediments were taken at 0-5 and 5-20 cm depths; three replicates were randomly taken from each plot and bulked into one sample per plot.

Plant and soil samples were transported to the laboratory, oven dried at 70°C (plants) and 105°C (soils), ground to powder and packed in plastic vials. Samples were wet digested prior to heavy metal analysis with a mixture of concentrated nitric (HNO3)-perchloric (CHlO4) acids following the method described in Sparks *et al.* (1996). Subsamples (0.2 g) were weighed into 15 ml test tubes in digestion (heating) blocks, 1.6 ml of concentrated HNO3 were added to each sample followed by 0.4 ml of concentrated CHLO4. Glass stoppers were used to seal the tops of tubes but still allowing for excess fumes to be released and samples were left in acid over night. On the following day, temperature was gradually raised from 100, 150 and 225 °C over a period of 6 hours until full digestion. Afterwards, tubes containing sample solutions were topped to 15 ml with distilled water and filtered through acid resistant filter paper.

Samples were then analysed for eight heavy metals including Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Cadmium (Cd) and Lead (Pb) using Fisons/VG PlasmaQuad II Inductively Coupled Plasma Mass Spectrometer (ICP-MS).

Statistical Analysis

Statistical analyses were performed using SPSS ver. 14.0, Mean differences in metal concentrations between soil depths and sites were compared using the Independent Sample t-test, Differences in metal concentration among individual plant components and decomposition periods were assessed using analysis of variance (ANOVA) with Tukey's pair-wise comparison test ($p = 0.05$, SPSS ver. 14).

Results and Discussion

Heavy Metal Accumulation in Shuaiba Mangrove System

Mangrove Tree Bioaccumilation

The heavy metal concentrations (μg g^{-1}) ranged from 0.10 to 29.98 for Cr, 3.47 to 67.27 for Mn, 39.54 to 3913 for Fe, 1.59 to 33.12 for Ni, 3.17 to 40.02 for Cu, 4.23 to 18.27 for Zn, 0.01 to 0.38 for Cd and from 0.38 to 5.01 for Pd (Table 1). The high metal concentrations were always found in fine roots while the leaves accounts for the lowest concentrations. Fine roots had significantly highest concentrations (μg g^{-1}) of Cr (29.98), Mn (67.27), Fe (3913.14), Ni (33.12) Cu (40.02), Zn (18.27), Cd (0.33) and Pb (5.01) compared to the rest of the components ($p < 0.05$). Leaves had metal concentrations less than half those of the roots, the leaf TF of the essential metals were 0.23 for Zn, 0.10 for Cu, 0.16 for Mn and 0.01 for Fe while the non-essential metal ratios were 0.11 for Pb, 0.20 for Ni, 0.03 for Cd and 0.15 for Cr (Table 1). Moreover, when metal values in plant componants where compared to the WHO/FAO standard values (2007), it was found that heavy metal concentrations were within the recommanded limites for all plant componants except for roots where values of Cr, Ni, and Cd were higher than the standard limites (Table 1) indicating immobility and limited transport of these metals to upper parts of the plant.

The higher heavy metal concentration in roots than in the sediment may reflect the continuous accumulation and filtration of metals in roots over a long period of time. The high metal concentration in roots may also indicate high bioavailability of metals in the sediment. In *Avicennia* species, air that is absorbed through aerial root lenticels can be transferred to the rhizosphere, oxidising the anaerobic sediment at the fine root level, reducing sulphide precipitation and lowering stability of iron plaque, thus allowing more metal exchange (Lacerda *et al.,* 1993). In a study of metal accumulation in various sediments, MacFarlane *et al.* (2003) noted an increase in Zn accumulation in roots in low pH sediments. Similarly, Clark *et al.* (1998) noted increases in metal exchange under low pH and oxidized (Eh >+100mV) conditions which attract the metal ions to the negative charges of the sediment particles. Moreover, Guo *et al.*(1997)*,* noted that the sediment Eh is another important parameter that can governs metal binding (Guo *et al.,* 1997). In addition, the sediment physical properties also might influence metal accumulation.

Table 1. Heavy metal concentration in µg g^{-1} (± SEM) (n=3) in *A. marina* tree components in a mangroves stand at Shuaiba region, Saudi Arabia.

Components	Mean concentration							
	Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb
Fine root	29.98 $(3.7)^{A}$	67.27 $(2.7)^{B}$	3913.14 $(208.2)^{E}$	33.12 $(1.7)^{H}$	40.02 $(4.1)^{I}$	18.27 $(0.8)^{J}$	0.33 (0.4)	5.01 $(0.08)^{K}$
Aerial root	4.35 $(0.3)^{a}$	4.00 $(0.2)^{b}$	115.06 $(29.3)^{e}$	4.07 $(1.9)^{h}$	3.37 $(0.9)^{i}$	1.63 $(0.7)^{j}$	0.07 (0.06)	ND
Stem	ND	3.47 $(0.6)^{b,C}$	271.14 $(42.5)^{e,F}$	2.14 $(0.5)^{h}$	3.17 $(1.3)^{i}$	ND	0.19 (0.05)	0.38 $(0.1)^{k}$
Branch	0.10 $(0.1)^{a}$	3.67 $(1.3)^{b,D}$	198.86 $(43.4)^{e,G}$	1.59 $(0.3)^{h}$*	4.63 $(1.2)^{i}$	ND	0.38 (0.2)	0.68 $(0.2)^{k}$
Leaves	4.53 $(0.22)^{a}$	11.14 $(0.5)^{b,c,d}$*	39.54 $(10.8)^{e,f,g}$*	6.74 $(3.2)^{h}$*	4.17 $(1.5)^{i}$	4.23 $(2.7)^{j}$*	0.01 (0.02)	0.57 $(0.5)^{k}$
TF	0.15	0.16	0.01	0.20	0.10	0.23	0.03	0.11
WHO/FAO (2007)	5	-	-	1.5	40	60	0.2	5

SEM: standard error of means; ND: below detectable limits; TF: translocation factor; * n=2; values in the same column with the same letters are significantly different from the mean values of the variables with the corresponding capital letters at 0.05 significant level. WHO/FAO are standard values.

Sediment Heavy Metal Accumulation

Heavy metal concentrations did not differ at the 5 and 5-20 cm depths ($p > 0.05$), the RCF of *A. marina* were generally high and root metal concentrations reach up to 16 times the concentrations in the sediments. RCF of the essential metals were 6.52, 9.23, 1.24 and 2.16 for Zn, Cu, Mn and Fe respectively, while those for the non-essential metals were 9.45, 1.21, 16.5 and 3.45 for Pb, Ni, Cd and Cr respectively. High RCF values indicate accumulative uptake of metals to rates that are much higher than those of the surrounding environment. In addition, when sediment heavy metals concentrations were compared to those of EU standards (2002), it was found that concentrations in the sediment were lower than the EU standard values (2002) indicating minimal contamination of Shuaiba mangrove sediments. The LCF values showed that much less of that sediment concentrations were translocated to leaves, the LCF of the essential metals were 1.51, 1, 0.44, and 0.26 for Zn, Cu, Mn and Fe respectively. While those for the non-essential metals were 1.1, 0.46, 0.50 and 0.34 for Pb, Ni, Cd and Cr respectively (Table 2).

Table 2 Distribution of heavy metals concentrations in µg g^{-1} (± SEM) in sediment, roots and leaves of *A .marina* mangroves growing in Shuaiba region on the Red Sea coast, Saudi Arabia.

Component	Mean concentration							
	Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb
Sediment	8.74 (1.1)	61.28 (4.9)	1810 (284)	27.42 (1.9)	4.16 (0.4)	2.8 (0.6)	0.02 (0.02)	0.53 (0.1)
EU (2002)	150	-	-	75	140	300	3	300
Fine roots	29.98 (3.7)	76.00 (8.3)	3913.14 (208.2)	33.12 (1.7)	38.39 (5.6)	18.27 (0.8)	0.33 (0.4)	5.01 (0.1)
Leaves	3.00 (1.5)	27.06 (15.9)	473.18 (433.7)	12.58 (6.1)	4.17 (1.5)	4.23 (2.7)	0.01 (0.02)	0.57 (0.5)
RCF	3.43	1.24	2.16	1.21	9.23	6.52	16.5	9.45
LCF	0.34	0.44	0.26	0.46	1.00	1.51	0.50	1.07

EU (2002) is the europian standard for soil heavy metals; RCF: root concentration factor; LCF: leaf concentration factor.

Litterfall Heavy Metal Input

After the decomposition period (128 days), there were no significant differences in final mass between Shuaiba and Yanbu sites ($p > 0.05$) (Fig. 1) with both sites having only 7.5 and 11% of mass remaining for Shuaiba and Yanbu respectively. However, Shuaiba litter lost 52% of its original mass in the first 64 days, significantly greater than that of Yanbu (44%)(*p* <0.05). In Shuaiba, the heavy metal concentrations in litter were stable throughout the decomposition period for most of the metals however, the concentrations for Mn, Zn, and Cu showed a significant increase in the first 64 days (Mn = 51.17 to 49.80 µg g-1; Zn = 2.13 to 25.2 µg g-1; Cu = 3.07 to 11.42 µg g-1) ($p < 0.05$) followed by a decrease until the end of the decomposition period (Mn= 49.80 to 15.50 µg g-1; Zn= 25.26 to 5.14 µg g-1; Cu= 11.42 to 7.81 µg g-1) (*p* <0.05) (Fig. 2 and 3). In addition, The estimated residence time in Shuaiba was 127 days and the tidal activities were within the range of 3-63 cm. The changes in the heavy metal concentrations in the decomposing leaves can be affected by a combination of leaching losses (due to high tidal levels), accumulation via absorption and microbial immobilization (Schierup and Larsen, 1981). The increase in Mn, Zn and Cu concentrations until day 64 and then decreased by day 128 may be due to the low tidal levels (at day 64) during August which had the lowest tidal levels of the year thus reducing leaching. This period was followed by a steady leaching until day 128 (October) when tidal levels where higher. Moreover, After 127 days (residence time) the concentration of the heavy metals in the removed litter was low indicating that litter that is removed from the forest floor contained low metal concentrations.

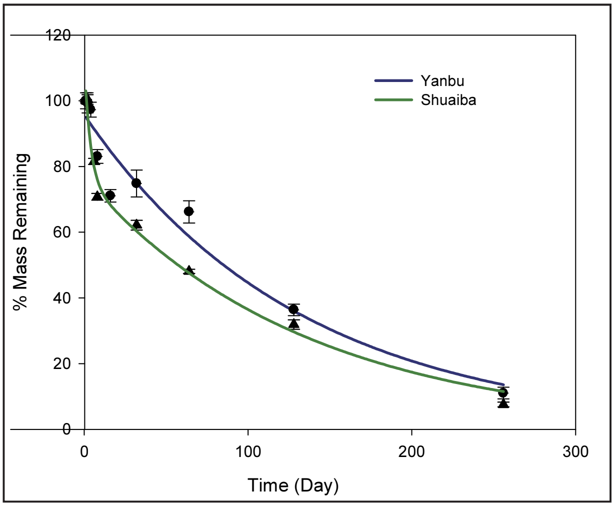

Fig. 1. Changes of the remaining litter mass over the decomposition period (256 days) in a mangrove stand in Shuaiba (▲) and Yanbu (●), Saudi Arabia (error bars are standard deviations).

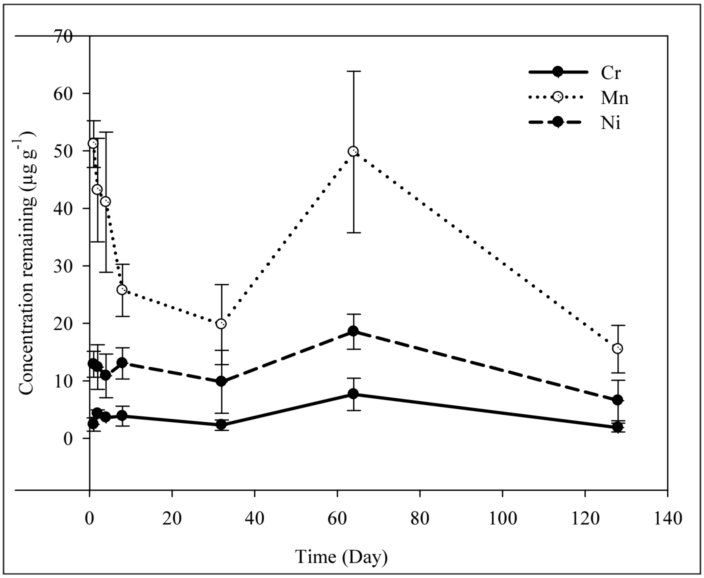

Fig. 2. Changes in Cr, Mn and Ni metal concentrations (µg g^{-1}) in decomposing litter in a mangrove stand in Shuaiba region, Saudi Arabia. (error bars are standard deviations).

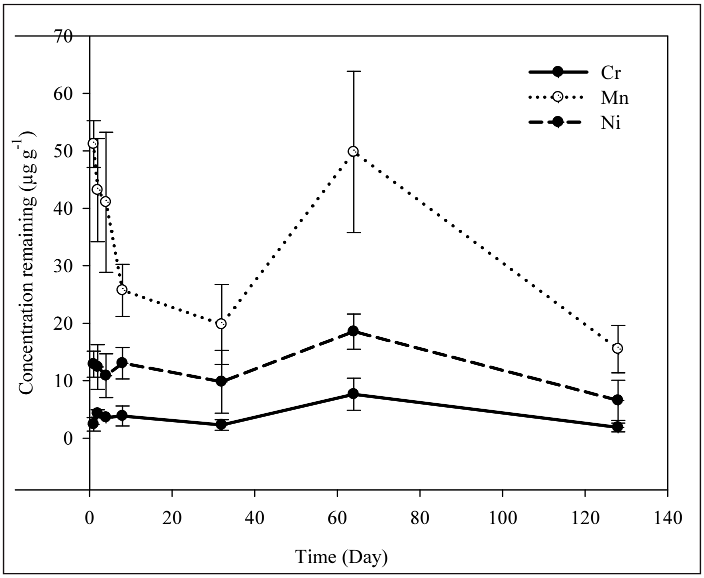

Fig. 3. Changes in Zn and Cu metal concentrations (µg g^{-1}) in decomposing litter in a mangrove stand in Shuaiba region, Saudi Arabia. (error bars are standard deviations).

Heavy Metal Accumulation in Yanbu Mangrove System

Mangrove Tree Bioaccumulation

In Yanbu, the heavy metal concentrations (µg g-1) ranged from 0.21 to 13 for Cr, 6.36 to 104.81 for Mn, 243.80 to 7911 for Fe, 2.13 to 29.17 for Ni, 5.09 to 31.52 for Cu, 3.17 to 16.77 for Zn, 0.20 to 0.33 for Cd and 0.35 to 7.32 for Pb (Table 2). Similar to Shuaiba, higher metal concentrations were found in fine roots compared to the other components; significantly highest fine roots concentrations (µg g-1) were of the metals: Mn (105), Fe (7912), Ni (29), Cu (31) and Pb (7) (p <0.05), while Cr and Zn concentrations were similar in fine and aerial roots. Moreover, when concentrations were compared to the WHO/FAO standards, it was found that heavy metal concentrations were below those of the standards except for Cr, Ni, Cd, and Pb where fine and aerial root concentrations were higher, However, heavy metal concentrations were always lower at the upper parts of the plant (Table 3). The translocation of metals to leaves was highly variable, for some metals concentrations in leaves account for more than half those of the roots, the TF values were 0.63 and 0.72 for Mn and Ni respectively. However, the concentrations were lower in other metals (0.22 for Cu, 0.05 for Fe, 0.18 for Cr and 0.03 for Pb), while Zn and Cd in leaves had concentrations that were below the detectable limits.

Sediment Heavy Metal Accumulation

Similar to Shuaiba, the metal concentrations in Yanbu were similar at the different sediment depths. when the sediment of the two sites were compared for concentration differences, it was found that Yanbu site had higher concentrations of Mn, Fe, Cu, Zn and Pb metals in sediment than Shuaiba (Table 4). Although Yanbu sediment had higher Mn, Fe, Cu, Zn and Pb concentrations than those of Shuaiba, the plant uptake appears to be lower than in Shuaiba. The concentrations of these metals in roots reach up to only 1.9 times the sediment concentrations with RCF values of 0.67, 0.94, 2.31, 1.23 and 1.9 for Mn, Fe, Cu, Zn and Pb respectively. The LCF values for those elements were low and reached only 50% of that of the sediments however, the Ni LCF was the only exceptionally highly concentrated in leaves reaching 85% of that in the sediment. The higher Mn, Fe, Cu, Zn and Pb metal concentrations in Yanbu sediment than in Shuaiba's may indicate higher exposure to these metals from the industrial effluences. Moreover, high metal concentrations in fine roots than in sediment may also indicate prolonged root accumulation; In addition, the low proportions of fine grains in Yanbu sediments (sandy loam) may also contributed to the lower metal accumulation. Fine particle sediment with high proportions of clay and silt tend to accumulate more metals than those with lower ratios due to its high surface area which can trap heavy metals and act as a substrate for organic matter which in turn can form complexes with heavy metals (Harbison, 1986; Prasad and Strzalka, 2002 and Marchand *et al.,* 2006).

Although the metal concentration in fine roots were higher than those of the sediment, the accumulation in fine roots was lower than in Shuaiba; Yanbu had much lower RCF and LCF ratios compared to Shuaiba which indicates efficient exclusion of metals at the root level. Except for Ni, the translocation of heavy metals from roots to leaves was generally low with translocation factors of less than 0.65. Nickel concentration was present at levels exceeding the normal concentrations in leaves although Ni concentrations in sediment were lower than frequently reported for contaminated sites (Kabata-Pendias and Pendias, 1984). Nickel is a common oil-related metal that can be present in high concentration in polluted areas and the high Ni concentration in the surface sediment may indicate precipitation of this metal from anthropogenic sources on the sediment surface. In addition, although heavy metal concentrations were higher than in Shuaiba, they were still lower than those previously reported for Yanbu sediments (Hashem *et al.,* 1993).

Litterfall Heavy Metal input

The patterns of heavy metal concentration in litterfall were quite different than that in Shuaiba. Initially, the concentrations in the decomposing leaves were constant for the first 64 days afterwards, the concentrations of Mn, Cu and Pb gradually increased until the end of the decomposition period (Mn = 31.59 to 55.46 µg g-1 ; Cu = 7.60 to 13.81 µg g-1 ; Pb = 0.93 to 3.87 µg g-1) (Fig. 4, 5 and 6). The residence time of litter on the forest floor was estimated to be 97 days and tidal activities were within the range of 6-88cm. the residence time of Yanbu litter correspond to the gradual increase of metal concentration in the litter increasing the likelihood of having high metal concentrations in the removed litter. The leaf litter in Yanbu lost 44% of its mass in the first 64 days of decomposition (Fig. 1) during which, the concentrations of all heavy metals generally increased to levels higher than those of the freshly fallen leaves with Fe representing the highest concentration.

Similar enrichment in decomposing litter of Fe, Mn Cu and Pb metals was previously reported (Schierup and Larsen, 1981 and Killingbeck *et al.,* 1982).

The increase in metal concentrations might be due to the precipitation and absorption of the metal ions, reduced ions under anoxic condition can be liberated from anoxic condition and oxidized (by the influence of the more frequent tidal levels) which then might be absorbed by litter particles (Lacerda *et al.,* 1993 and Lacerda, 1998). In addition, the tidal waters carrying organic particles are negatively charged waters that can attract heavy metal cations which in turn can be absorbed by litter via ion-exchange (Silva *et al.,* 2006).

Table 3. Heavy metal concentration in µg g^{-1} (± SEM) (n=3) in *A. marina* tree components in a mangroves stand at Yanbu city, Saudi Arabia.

Components	Mean concentration							
	Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb
Fine root	13.00 (0.4)^{A}	104.81 (4.3)^{C}	7911.57 (1252.3)^{G}	29.17 (3.6)^{H}	31.52 (2.4)^{L}	16.77 (0.52)^{M*}	0.33 (0.02)	7.32 (1.8)^{N}
Aerial root	11.94 (3.5)^{B}	29.84 (6.2)^{c,D}	250.42 (84.2)^{g}	3.64 (0.9)^{h,I*}	6.79 (0.6)^{l}	7.79 (2.6)	0.32 (0.2)	0.46 (0.2)^{n}
Stem	0.21 (0.02)^{a,b*}	6.36 (1.7)^{c,d,E}	284.23 (64.7)^{g}	2.13 (0.2)^{h,J}	5.09 (1.8)^{l}	ND	0.19 (0.01)	0.56 (0.2)^{n}
Branch	0.35 (0.1)^{a,b}	6.52 (0.8)^{c,d,F}	243.80 (48.0)^{g}	3.28 (0.3)^{h,K}	5.45 (1.5)^{l}	3.17 (0.9)^{m*}	0.20 (0.01)	0.59 (0.05)^{n}
Leaves	2.37 (0.5)^{a,b}	65.95 (4.1)^{c,d,e,f}	375.39 (40.8)^{g}	21.10 (2.6)^{i,j,k}	6.83 (2.9)^{l}	ND	ND	0.22 (0.2)^{n}
TF	0.18	0.63	0.05	0.72	0.22	-	-	0.03
WHO/FAO (2007)	5	-	-	1.5	40	60	0.2	5

SEM: standard error of means; ND: below detectable limits; TF: translocation factor; * n=2; values in the same column with the same letters are significantly different from the mean values of the variables with the corresponding capital letters at 0.05 significant level.

Table 4. Heavy metal concentration in µg g^{-1} (± SEM) of *A. marina* sediments in two mangrove stands at Shuaiba and Yanbu regions, Saudi Arabia.

Site	Mean concentration						
	Cr	Mn	Fe	Cu	Zn	Cd	Pb
Shuaiba	8.75 (1.1)	61.33 (4.9)^{A}	1791.66 (284)^{B}	4.13 (0.4)^{C}	2.76 (0.6)^{D}	0.02 (0.02)	0.53 (0.1)^{E}
Yanbu	11.51 (2.1)	150.14 (15.7)^{a}	8825.94 (3307)^{b}	13.97 (4.0)^{c}	13.52 (2.6)^{d}	0.20 (0.1)	3.84 (0.8)^{e}

SEM: standard error of means; values in the same column with the same letters are significantly different from the mean values of the variables with the corresponding capital letters at 0.05 significant level.

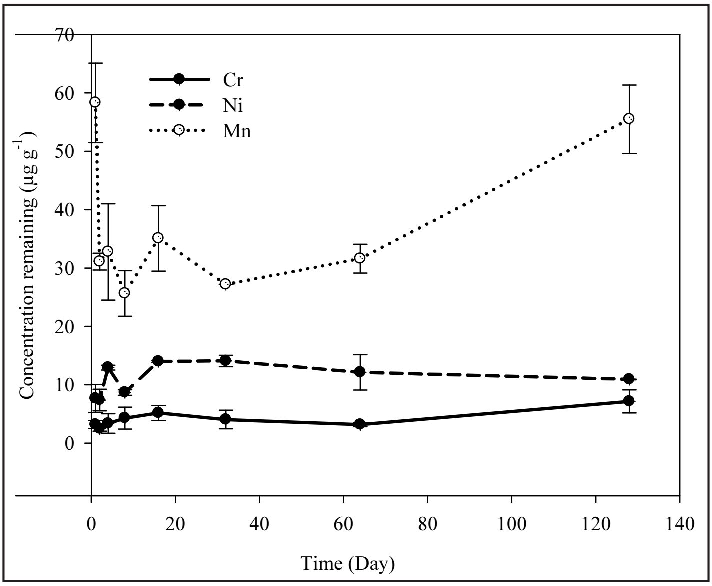

Fig. 4. **Changes in Cr, Ni and Mn metal concentrations (µg g^{-1}) in decomposing litter in a mangrove stand in Yanbu region, Saudi Arabia. (error bars are standard deviations).**

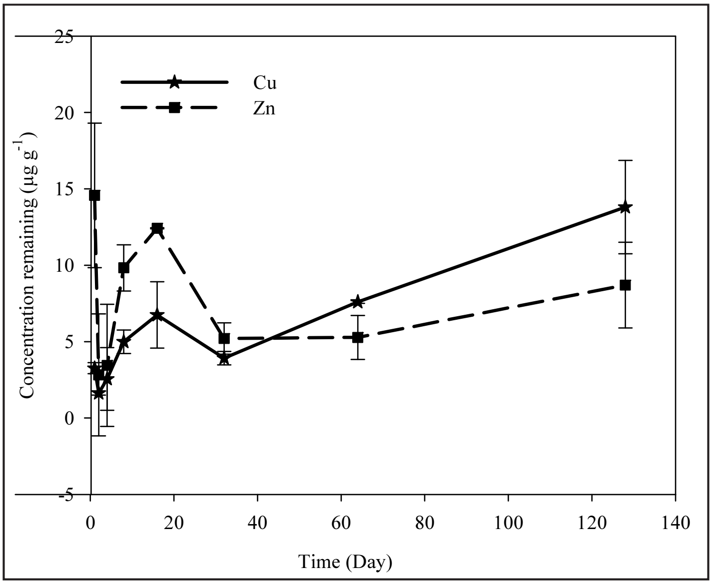

Fig. 5. **Changes in Cu and Zn metal concentrations (µg g^{-1}) in decomposing litter in a mangrove stand in Yanbu region, Saudi Arabia. (error bars are standard deviations).**

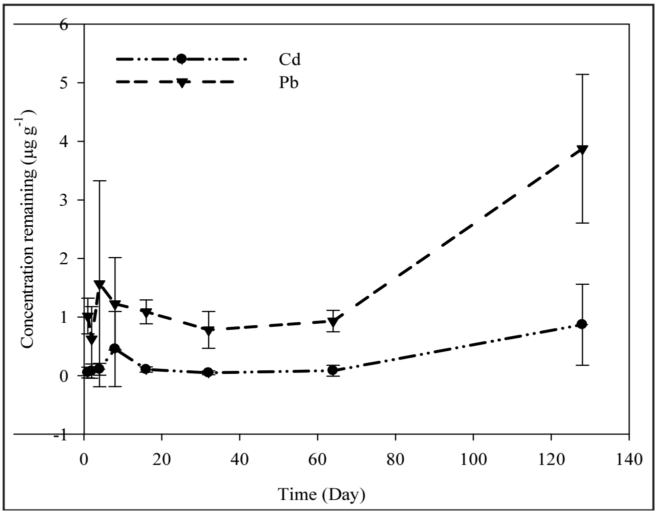

Fig. 6. **Changes in Cd and Pb metal concentrations (µg g^{-1}) in decomposing litter in a mangrove stand in Yanbu region, Saudi Arabia. (error bars are standard deviations).**

The residence time of litter on the forest floor in Yanbu (97 days) was shorter than that at Shuaiba and may be influenced by a higher tidal levels in Yanbu (88 cm) than in Shuaiba (63 cm). In addition, the natural setting of the fringe Yanbu mangroves allow tidal water to inundate the site more frequently than in the Shuaiba basin mangroves which can contribute to the shorter residence time.

Heavy Metal Accumulation in Red Sea Mangrove Systems

Generally, heavy metals in mangrove trees were accumulated most in fine roots, leaves accounts for the least metal concentrations which contributed to the low metal input through litterfall. When metal concentrations in leaves were compared to those reported in the literature (Table 5), it was found that the metal concentrations in the leaves of the current study were below those reported thus, lower annual input of metals to the sediment. The low metal input through litterfall suggest that a significant amount of metal input to the system came through the decomposition of fine roots which contain higher metal concentration than other plant components. Moreover, fine roots are known for their high turnover rate, and incorporation into soil is a slow process in such anoxic conditions as a result of the slow decomposition and low microbial activities. The slow decomposition of the metal-enriched roots can release a significant amount of highly concentrated metals back into the sediment. Therefore it is of interest to investigate the contribution of metal input through fine roots into the sediment pool. Such an estimate would aid in assessing the role of fine roots in the heavy metal dynamics in the mangrove systems.

Table 5. Comparison of heavy metal concentrations (µg g^{-1}) of leaves in mangrove systems from different publications.

Source	Location	Species	Metal concentration (µg g^{-1})							
			Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb
Current study	Saudi Arabia	*A. marina*	2.4-4.5	11.1-65.9	39.5-375.4	6.7-21.1	4.2-6.8	0-4.23	0-0.01	0.22-0.57
Saifullah *et al.* (2004)	Pakistan	*A. marina*	-	-	309.8	-	-	-	-	-
MacFarlane *et al.* (2003)	Australia	*A. marina*	-	-	-	-	0.14	0.38	-	0.02
Sadiq and Zaidi (1994)	Saudi Arabia	*A. marina*	-	-	-	-	4.4	11	-	6.9
Defew *et al.* (2005)	Panama	*Laguncularia racemosa*	3.7	-	-	-	-	35.8	-	6.2

The sediment is an important pool in mangrove systems because of its ability to retain heavy metals, and it is frequently reported in literature as an indicative of a system's status and health. The sediment heavy metals of the current study were comparable with or below those reported for mangrove sediments (Table 6). When the concentrations compared to those of the same region (*e.g.* Shriadah, 1998; Sadiq and Zaidi, 1994 and Hashem, 1993) it was also found that concentrations were less than previously reported. In Yanbu, with the exception of Fe, the sediment concentrations were lower than those reported in Hashem (1993), while only Mn, Fe, Ni and Cu had higher concentrations than those reported in Sadiq and Zaidi (1994). From these findings it can be concluded that the mangrove systems in the Shuaiba and Yanbu regions are clean compared to other polluted sites around the world. In Yanbu, several violations of industrial discharges have been reported (*e.g.* Paimpillil *et al.,* 2002 and Ahmad *et al.,* 2008). Ahmad *et al.* (2008) mentioned that many types of pollutants are discharged into coastal areas in excessive concentrations such as hydrocarbon compounds and thus present another form of pollution for Yanbu mangroves. In addition other organic and thermal pollutants were reported to significantly affect mangrove systems in other parts of the Red Sea coast (*e.g.* Mandura 1997 and Aleem, 1990). Thus investigation of possible contamination, runoff from domestic and industrial sewage from populated areas on the Red Sea coast is recommended in order to assess the possible contamination in the mangrove systems on the Red Sea coast.

Table 6. Comparison of heavy metal concentrations (µg g^{-1}) in mangrove sediments from different publications.

Source	Location	Species	Metal concentration (µg g^{-1})							
			Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb
Current Study	Saudi Arabia	*A. marina*	8.7-11.7	61.3-156.7	1810-8373	27.4-24.8	4.2-13.6	2.8-13.6	0.02-0.2	0.5-3.9
Awal *et al.* (2009)	Sundarbans-(Bangladesh)	Multi species	15.7	436.8	173890	76.1	10.5	73.6	0.55	19.3
Zöckler and Bunting (2006)	Bangladesh	-	19.5-46.1	-	-	15.9-44.6	6.9-31.6	24.3-76.0	0.01-0.006	8.0-15.7
MacFarlane *et al.* (2003)	Australia	*A. marina*	-	-	-	-	26.8-196.5	133.0-386.1	-	53-177.8
Shridah (1998)	UAE	*A. marina*	10.2-14.1	39.9-111	-	18.0-76.3	6.3-9.2	9.0-13.2	4.7-5.2	20.4-37.3
Sadiq and Zaidi (1994)	Saudi Arabia	*A. marina*	2.4-12.7	2.0-69.3	645-3600	1.9-18.1	0.14-3.8	2.2-17.1	0.2-3.0	6.1-18.8
Hashem (1993)	Yanbu-Saudi Arabia	*A. marina*	-	-	43.1	-	31	13.3	2.3	26.1
IUCN/MEPA (1987)	Pakistan	*A. marina*	1.5-8.6	-	-	-	2.3-14.7	-	0.04-0.15	3.4-15.6

Ranges of the current study are for Shuaiba andYanbu respectively; single values are mean concentrations.

Conclusions

The Shuaiba mangroves contain relatively lower concentrations of heavy metals than Yanbu due to minimal exposure to anthropogenic sources. However, these concentrations at Yanbu were below the commonly reported for other polluted sites. The current findings suggest that the mangrove systems investigated are not under heavy metal pollution pressure although metals are accumulated within the mangrove systems. However, further investigation of possible anthropogenic contamination in other mangrove stands is crucially important for assessing the environmental health of the individual mangrove systems on the Red Sea coast. In addition, it is equally important to investigate the sources of pollution in the mangrove systems, violations of industrial discharge regulations and to initiate environmental monitoring programs.

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التلوث بالعناصر الثقيلة في نظم غابات الشورى على ساحل البحر الأحمر بالمملكة العربية السعودية

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المستخلص. تمت دراسة انتقال وحركة ثمان من العناصر الثقيلة في بيئة غابات الشورى في منطقتي الشعيبة وينبع الصناعية على ساحل البحر الأحمر، وهي الكروم (Cr)، والمنجنيز (Mn)، والحديد (Fe)، والنيكل (Ni)، والنحاس (Cu)، والزنك (Zn)، والكادميوم (Cd)، والرصاص (Pb)، حيث تم تقدير تراكيز هذه العناصر في الأشجار، والتربة و في الطرح الخضري. ووجد أن أعلى تراكيز للعناصر الثقيلة كان في التربة، ثم في الأشجار، ووجد أن أقل من ٣,٥٪ من هذه العناصر يتم تدويرها وإعادتها إلى التربة عن طريق الطرح الخضري، منها أقل من ١٪ تتم إزالته من على أرض الغابة عن طريق حركة المد والجزر. وبشكل عام وجد أن تراكيز العناصر في منطقة ينبع الصناعية كانت أعلى منها في منطقة الشعيبة ولكنها مازالت أقل من النسب التقديرية للمناطق الملوثة عالميا. توصي الدراسة بضرورة متابعة وتقييم مستوى الملوثات في غابات الشورى القريبة من المناطق الصناعية والمدن الكبيرة وكذلك القريبة من التجمعات السكانية الأخرى.

الكلمات المفتاحية: Avicennia marina، ساحل البحر الأحمر، التخزين الحيوي للعناصر الثقيلة، التلوث الساحلي، تلوث التربة الرسوبية.