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Monitoring Trace Metal Contaminants in Green Mussel, *Perna viridis* from the Coastal Waters of Karnataka, Southwest Coast of India

Geetha Sasikumar, P. K. Krishnakumar, G. S. Bhat

Mangalore Research Centre of Central Marine Fisheries Research Institute, Post Box No. 244, Mangalore 575 001, Karnataka, India

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Abstract. The green mussel (*Perna viridis*) is widely distributed in the coastal waters of Asia and is used in mussel watch programmes for monitoring environmental contaminants throughout the region. Green mussels representing different size groups and habitats were sampled from their natural beds at 28 locations in the inshore waters of Karnataka (southwest coast of India) to analyze the tissue concentrations of Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn. Tissue concentrations of Cr, Cu, Fe, and Pb were significantly higher in smaller mussels than in the larger size group. Significantly higher concentrations of Cr, Cu, Fe, Mn, and Ni were observed in mussels sampled from intertidal beds when compared to mussels from the subtidal beds. The sampling sites were categorized into industrial sites (IS), urban sites (US), and nonurban sites (NS) based on principal component analysis of metal concentrations in mussel. Spatial variations in tissue concentrations of all metals were observed except for Zn. Generally, the levels of toxic trace metals like Pb, Cd, Ni, and Cr in the whole tissue of *P. viridis* were within safe limits throughout the coast of Karnataka. However, relatively high concentrations of Cd, Cr, and Pb were observed in the whole tissue of green mussels collected from the industrial sites (IS), which may be derived from a variety of anthropogenic activities.

Trace metals in coastal waters are derived from a variety of natural and anthropogenic sources. Urban and industrial developments along the coastal areas, rivers, and estuaries contribute to the major part of the anthropogenic metal load of the sea (Ridwig *et al.* 2003; Cobelo-Garcia *et al.* 2004). Trace metals can be bioaccumulated in aquatic organisms. Due to the concerns over this accumulation and their toxic effects to humans consuming these organisms, monitoring programmes for metals in environmental (biotic and abiotic) samples have been widely established and implemented. The bioaccumulation of metals in benthic macroinvertebrates can provide an indication of the extent and magnitude of environmental contamination that is temporarily introduced via the water column and sediment. Thus, biomonitoring by employing living organisms such as mussels as sensors plays a vital role in governmental and industrial strategies to identify, assess, control, and reduce pollution problems (Krishnakumar *et al.* 1994, 1995).

The criteria by which organisms are accepted as biological indicators for the assessment of contamination were proposed more than 25 years ago and remain unchanged (Phillips 1976a, b; Fowler and Oregioni 1976). Marine bivalves, especially mussels, are widely used as sentinel organisms for coastal biomonitoring programmes due to their sessile nature, mode of feeding, ability to accumulate contaminants from the environment, and availability for human consumption. Distribution of trace metals in the whole tissue and/or byssus threads of mussels has been extensively studied from both ecotoxicological and seafood safety points in several countries (Phillips 1976a, b; O'Conner 1992; Krishnakumar *et al.* 1994, 1995, 1997; Glynn *et al.* 2003; Nicholson and Szefer 2003; Szefer *et al.* 2004; Liu and Kueh 2005).

Green mussel (*Perna viridis*) is widely distributed in the coastal waters of Asia and is used in mussel watch programmes for monitoring environmental contaminants in the region (Lakshmanan and Nambisan 1983; Krishnakumar *et al.* 1990, 1998; Radhakrishnan 1993; Tewari *et al.* 2000, 2001; Monirith *et al.* 2003). Green mussels distributed throughout the west coast of India contribute a significant fishery of commercial importance. Along the Karnataka coast, natural mussel beds are located mostly in the subtidal zones attached to rocky substratum. Intertidal mussel beds are also found along the rocky coast in some areas. Besides the traditional fishery, the area also provides great potential for mussel mariculture as demonstrated by Central Marine Fisheries Research Institute (Mohamed *et al.* 1998). Being an important candidate species for mariculture (Nayar *et al.* 1980), they are farmed in many areas along the west coast of India as part of a rural development programme (Appukuttan *et al.* 2000).

Inshore waters of Karnataka (west coast of India) lying adjacent to Mangalore and Karwar receive treated effluent from several industrial sources including a caustic soda plant, fertilizer plant, iron ore processing plants, dyes and pigment processing plants, petroleum refinery, and other sources. About 12 towns located near the 300–km-long coastline discharge untreated sewage amounting to approximately 30 t/day directly into the coastal waters (CPCB 1996). The Central

Correspondence to: P. K. Krishnakumar; *email:* kkumarpk@touchtelindia.net

Pollution Control Board of India has identified two cities, Karwar and Mangalore, on the Karnataka coast as pollution "hotspots" (CPCB 1996). Additionally, the coastal ecosystems on the southern part of the coast have been identified as "stressed" by anthropogenic activity (TERI 1999).

The distributions of heavy metals in the whole tissue of green mussel have been reported previously from the urban areas of Karnataka (Krishnakumar and Pillai 1990; Krishnakumar *et al.* 1990, 1998). However, detailed information on levels of toxic trace metals in natural populations of green mussels with varying size groups and categories of sites from the Karnataka coast is lacking. Hence the present study was planned to assess the levels of selected trace metals (Cd, Cu, Cr, Fe, Mn, Ni, Pb, and Zn) in the whole tissue of green mussel (*P. viridis*) collected from various categories of sites covering 28 sampling stations, including islands, subtidal and intertidal beds covering a 300-km coastline of Karnataka State, on the west coast of India.

Materials and Methods

Characteristics of the Study Area

The study area extending from Karwar in the north to Someshwara in the south (Fig. 1) consists of three coastal districts: Dakshina Kannada, Udupi, and Uttara Kannada. The coastal area, which is blessed with 14 perennial rivers, is increasingly subjected to urban development. Stations 2, 3, and 4 are located in the industrial belt where a fertilizer plant, iron ore processing plants, dye and pigment processing plants, petroleum refinery, among others, are located (Fig. 1). A major port is located between these stations at Panambur about 15 km north of Mangalore. Stations 8, 11, and 16 are located inside Fisheries harbours (Fig. 1).

Mussel Sampling

Mussel samples from their natural populations were collected from 28 locations during January 2002 (Fig. 1). Depending upon availability, mussels were collected from three different depths, 0 m (intertidal), 3.4 m (3–3.8 m), and 5.4 m (5–5.8 m), by engaging local divers and transported to the laboratory. The latitude and longitude of the sampling stations were marked using portable Global Positioning System (Garmin GPS, Model XL 12) with an accuracy of ±5 m. The shellfish were depurated overnight in clean and filtered seawater. The length of each individual mussel was measured and sorted according to their shell length before further analysis. The mussels were sorted as small (S) <50 mm, medium (M) 50–80 mm, and large (L) >80 mm.

Trace Metal Analysis

Mussel samples were rinsed with distilled water, byssal threads removed, and wet shucked. Depending upon the availability, from each category (site, size, and depth), the whole tissue samples from 10 mussels were pooled, minced using sharp stainless steel scissors, and homogenized using a plastic spatula. Three such batches were used for the analysis. Approximately 1–2 g of tissue was digested with 10 ml mixture of HNO_3 and H_2O_2 (1:1 ratio) following standard procedure (Robisch and Clark 1993). The heavy metals in the digested samples were determined by Atomic Absorption Spectrophotometry with either air-acetylene flame (zinc) or graphite furnace (copper, cadmium, nickel, lead). The results were expressed in μg g^{-1} wet tissue weight. Blanks and standards were digested with each sample set to provide quality control. The accuracy of the method was verified (10 replicates) using standard reference material (fish tissue, MA-B3/TM) obtained from the International Laboratory of Marine Radioactivity, IAEA. Recoveries were above 90% for all the trace metals measured.

Statistical Analysis

One-way analysis of variance (ANOVA) was utilized to study the effect of size of mussels and depth of collection on the variations in concentrations of metals in mussel tissue (SPSS 12.00). After assessing the significance of the averages for each metal, range tests (Tukey's-b and S-N-K) were carried out to obtain homogeneous subsets of means. The data set from homogeneous size groups were pooled and subjected to principal component analysis for grouping of sampling sites.

Results

Size-Dependent Trend

The mean concentrations of Cd, Cr, Cu, Fe, Mn, Ni, and Pb in the whole tissue (μg g^{-1} wet wt) of *P. viridis* in different size groups along Karnataka coast are shown in Table 1. The tissue concentration of Cd in smaller mussels varied from 0.24 to 3.49, Cr from below detectable level (nd) to 0.40, Cu from nd to 1.67, Fe from 35.52 to 235.60, Mn from 1.91 to 8.77, Ni from nd to 1.87, Pb from nd to 1.95, and Zn from nd to 16.91 μg g^{-1} wet wt. The tissue concentration of Cd from medium-sized mussels varied from 0.28 to 1.95, Cr from nd to 0.46, Cu from nd to 1.75, Fe from nd to 145.46, Mn from 2.62 to 8.57, Ni from nd to 1.47, Pb from nd to 1.96, and Zn from nd to 17.36 μg g^{-1} wet wt. Among the larger mussels, the tissue concentration of Cd varied from 0.52 to 1.55, Cr from nd to 0.12, Cu from nd to 1.843, Fe from 14.56 to 68.21, Mn from 2.59 to 6.88, Ni from nd to 2.89, Pb from nd to 0.64, and Zn from 6.76 to 13.23 μg g^{-1} wet wt.

Variations in the trace metal concentrations in tissues of different sized mussels from the sampling sites are presented in Table 2. Sizewise distributions of Cr, Cu, Fe, and Pb in the whole tissue of mussels were statistically significant ($p < 0.05$) by ANOVA. Tissue concentrations of Cr, Cu, Fe, and Pb were significantly lower (Table 2) in larger mussels than in the smaller size groups ($p < 0.05$, S-N-K and Tukey s-b). No significant differences among size groups in Cd, Mn, Ni, and Zn concentrations were observed.

Tidal Effect

In the present study, the Cr, Cu, Fe, Mn, and Ni showed significantly higher levels in mussels collected from intertidal beds (Fig. 2) than in mussels collected from subtidal beds. There was no significant difference between the concentrations of Cd, Pb, and Zn in mussels from intertidal and subtidal beds. However, the mean concentrations of Pb and Zn were higher in intertidal mussels and that of Cd was higher in subtidal mussels.

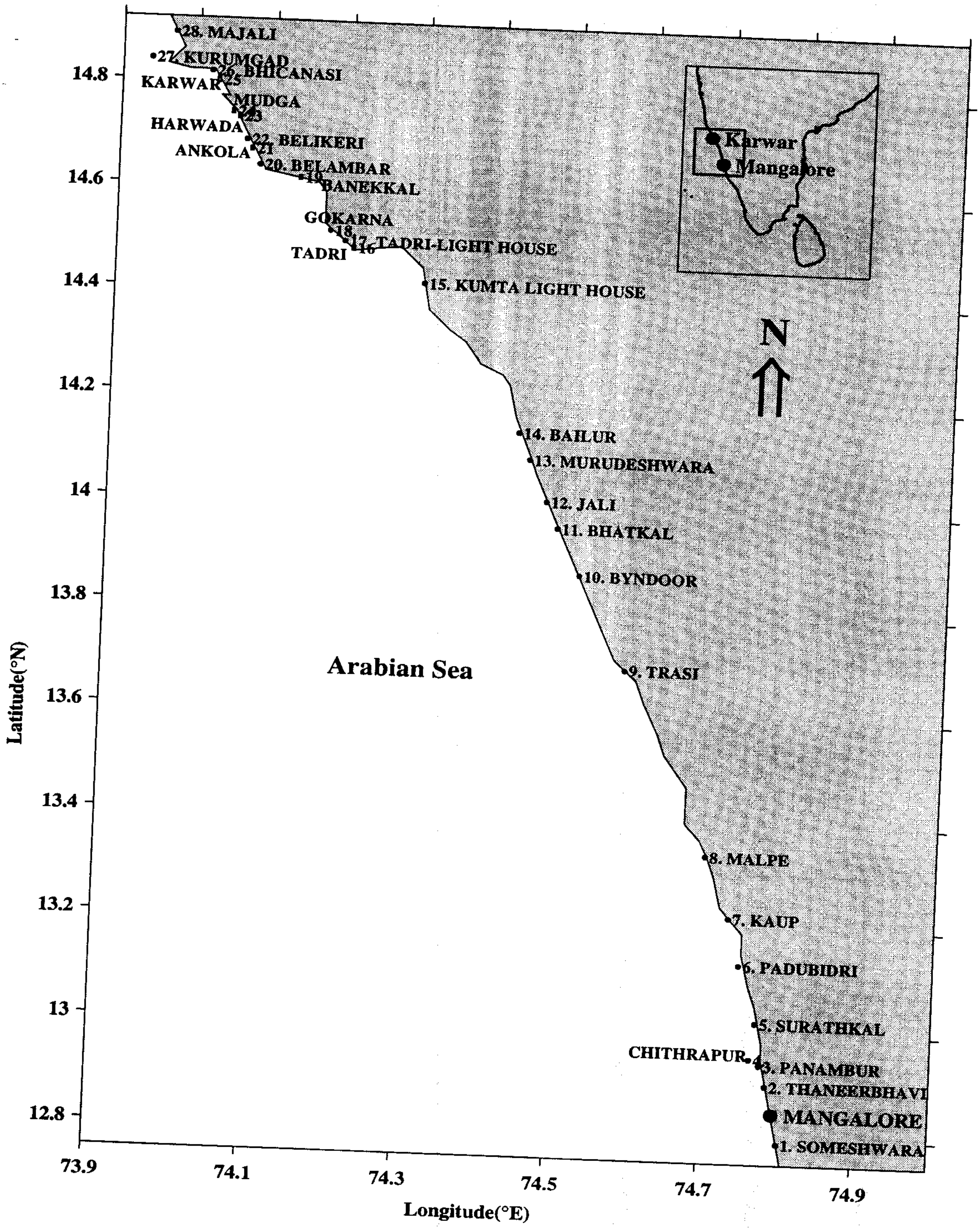

Fig. 1. Map showing the mussel sampling sites in the coastal waters of Karnataka (west coast of India)

Spatial Trends

The mean concentrations of Cd, Cr, Cu, Fe, Mn, Ni, and Pb in the whole tissue (μg g^{-1} wet wt) of smaller and medium-sized (homogeneous size groups as shown in Table 2) mussels from subtidal beds were only used for grouping of sampling sites. In Fig. 3, the results of the principal component analysis (PCA) are presented in a scatterplot. The first two principal components (PC1 and PC2) are responsible for some 49.7% of the data scatter. Ordination on PC1 (variance 28.9%) mostly corresponds to samples collected from the industrial sites, stations 2, 3, 4, in addition to a Fisheries harbour (Station 11) and urban sites nos. 24, 25, 26, 27. There was strong separation of the northern sites from the southern sites. PC2 (variance

Table 1. Concentration of trace metals in the whole tissue (μg/g wet wt) of green mussel, *Perna viridis*, belonging to different size groups [Small (S) ≤50 mm, Medium (M) 50–80 mm, Large (L) >80 mm] collected from the coastal waters of Karnataka, west coast of India (mean ± SD)

Site code	Size	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
1	S	1.10 ± 0.29	nd	nd	35.51 ± 63.28	5.13 ± 2.08	nd	nd	9.74 ± 0.93
	M	0.75 ± 0.40	nd	nd	11.75 ± 23.51	5.23 ± 2.71	nd	nd	12.74 ± 2.61
	L	0.51 ± 0.23	nd	0.39 ± 0.46	21.53 ± 16.41	3.29 ± 0.23	0.48 ± 0.96	nd	11.44 ± 1.49
2	S	0.53 ± 0.16	0.23 ± 0.01	0.08 ± 0.12	90.00 ± 62.37	3.56 ± 1.04	1.23 ± 0.16	1.94 ± 0.04	9.71 ± 0.48
3	M	1.44 ± 0.03	0.46 ± 0.18	0.56 ± 0.11	91.65 ± 36.42	2.61 ± 0.54	0.23 ± 0.16	1.95 ± 0.02	10.77 ± 1.51
4	S	3.48 ± 0.27	0.28 ± 0.08	1.02 ± 0.16	86.37 ± 25.32	3.25 ± 0.74	0.53 ± 0.23	1.90 ± 0.08	9.48 ± 0.50
5	S	0.55 ± 0.17	nd	0.19 ± 0.30	94.49 ± 134.54	1.91 ± 2.34	nd	nd	8.57 ± 0.81
	M	1.51 ± 0.24	0.05 ± 0.09	0.06 ± 0.18	31.49 ± 84.27	3.06 ± 1.64	nd	nd	9.36 ± 4.34
6	M	1.60 ± 0.19	nd	nd	60.25 ± 79.06	3.77 ± 0.17	nd	nd	7.45 ± 1.92
7	S	0.68 ± 0.12	nd	0.54 ± 0.27	85.34 ± 39.95	3.54 ± 0.22	0.71 ± 0.13	nd	10.57 ± 2.08
8	M	1.32 ± 0.36	nd	nd	nd	3.41 ± 0.05	nd	nd	5.96 ± 0.92
9	M	1.80 ± 0.07	nd	0.89 ± 0.07	38.04 ± 0.11	2.63 ± 0.30	nd	0.39 ± 0.23	12.31 ± 0.19
	L	1.36 ± 0.19	nd	nd	14.55 ± 17.10	2.59 ± 1.11	nd	nd	6.75 ± 2.3
10	M	1.23 ± 0.03	nd	nd	122.32 ± 34.61	8.27 ± 0.57	nd	nd	8.52 ± 1.65
	L	1.20 ± 0.53	0.012 ± 0.03	0.05 ± 0.13	45.80 ± 46.75	6.29 ± 1.6	0.04 ± 0.10	nd	9.47 ± 1.62
11	S	1.16 ± 1.61	0.39 ± 0.13	0.45 ± 0.55	48.36 ± 19.04	6.41 ± 0.52	nd	1.81 ± 0.01	8.02 ± 0.58
12	L	1.55 ± 0.07	nd	nd	61.82 ± 19.17	6.34 ± 0.85	nd	0.52 ± 0.06	8.70 ± 2.63
13	L	1.44 ± 0.06	nd	nd	53.40 ± 46.86	4.37 ± 0.25	nd	nd	8.57 ± 1.79
14	L	1.14 ± 0.08	nd	nd	68.21 ± 30.97	4.89 ± 0.74	nd	0.64 ± 0.08	9.12 ± 2.17
15	M	1.95 ± 0.35	nd	nd	93.53 ± 17.22	7.32 ± 0.31	nd	1.45 ± 0.64	nd
16	M	1.60 ± 0.28	nd	0.21 ± 0.30	61.65 ± 77.91	5.66 ± 0.59	nd	1.53 ± 0.51	14.48 ± 20.48
17	M	1.95 ± 0.49	0.06 ± 0.08	1.15 ± 1.63	125.45 ± 26.42	7.41 ± 2.63	nd	0.10 ± 0.01	17.02 ± 24.08
18	S	0.37 ± 0.10	nd	1.18 ± 0.31	86.57 ± 33.87	6.19 ± 1.69	nd	nd	11.51 ± 6.75
19	M	1.25 ± 0.07	nd	0.88 ± 0.10	106.28 ± 5.22	3.75 ± 0.10	nd	0.61 ± 0.06	12.52 ± 17.71
20	M	1.16 ± 0.52	nd	1.00 ± 0.01	118.93 ± 16.35	4.26 ± 0.17	nd	0.67 ± 0.28	11.87 ± 16.8
21	S	0.24 ± 0.05	0.14 ± 0.13	1.33 ± 0.06	186.52 ± 57.2	5.69 ± 0.86	nd	nd	16.91 ± 4.98
22	M	0.32 ± 0.01	nd	0.89 ± 0.17	117.06 ± 29.55	5.22 ± 0.44	nd	nd	17.35 ± 9.37
23	S	1.05 ± 0.07	nd	0.75 ± 1.07	235.60 ± 22.49	7.02 ± 0.01	nd	0.86 ± 1.22	nd
24	M	0.27 ± 0.12	0.27 ± 0.20	1.55 ± 0.37	145.45 ± 66.21	7.14 ± 1.75	0.58 ± 0.44	nd	9.12 ± 1.81
25	M	1.19 ± 0.03	0.10 ± 0.10	1.75 ± 0.34	39.55 ± 13.75	8.57 ± 1.89	1.46 ± 1.51	nd	10.92 ± 1.58
	L	1.54 ± 0.08	0.12 ± 0.06	1.84 ± 0.47	39.08 ± 7.63	6.88 ± 0.51	2.88 ± 0.87	nd	13.22 ± 2.11
26	S	0.48 ± 0.61	0.18 ± 0.07	1.66 ± 0.08	48.39 ± 2.26	7.64 ± 0.18	1.40 ± 0.15	nd	14.07 ± 1.06
27	S	0.28 ± 0.05	0.14 ± 0.06	1.38 ± 0.19	40.69 ± 1.69	8.49 ± 0.43	1.87 ± 0.01	nd	7.47 ± 0.90
28	S	1.70 ± 0.14	nd	0.35 ± 0.49	92.43 ± 40.7	8.77 ± 1.12	nd	1.23 ± 0.15	10.05 ± 0.08

nd, not detectable.

Table 2. Trace metal concentrations (μg/g wet wt) in the whole tissue (mean ± SD) of different sized mussels (*Perna viridis*)

Size group	Cd	Cr*	Cu*	Fe*	Mn	Ni	Pb*	Zn
Small	1.08 ± 0.98	0.09^{a} ± 0.13	0.60^{a} ± 0.62	81.04^{a} ± 74.7	5.24 ± 2.39	0.33 ± 0.57	0.5 ± 0.82	9.72 ± 3.84
Medium	1.26 ± 0.52	0.07^{ab} ± 0.14	0.60^{a} ± 0.73	64.89^{ab} ± 66.4	5.13 ± 2.55	0.24 ± 0.71	0.25^{ab} ± 0.53	10.46 ± 7.3
Large	1.19 ± 0.46	0.01^{b} ± 0.04	0.23^{b} ± 0.53	40.29^{b} ± 35.9	5.05 ± 1.91	0.31 ± 0.87	0.09^{b} ± 0.22	9.49 ± 2.38

* Significantly different groups marked ($p < 0.05$) with letters a, b, and c.

20.8%) allowed us to differentiate between the industrial and urban sites from the nonurban sites. The sampling sites were categorized into industrial sites (IS) urban sites (US), and nonurban sites (NS) depending upon the PCA.

Table 3 lists the mean concentration of Cd, Cr, Cu, Fe, Mn, Ni, and Pb in the whole tissue (μg g^{-1} wet wt) of *P. viridis* from the different categories of sampling sites along Karnataka coast. Among the three different categories of sites, the mean concentration of Cd ranged from 0.70 to 2.02, Cr from 0.012 to 0.33, Cu from 0.36 to 1.63, Fe from 70.83 to 80.55, Mn from 3.81 to 8.01, Ni from 0.02 to 1.26, Pb from below detectable level (ND) to 1.9, and Zn from 9.49 to 10.36 μg g^{-1} wet wt. Maximum concentrations of Cd, Cr, Fe, and Pb were recorded in the industrial areas (IS).

The variability of trace metals in different categories of sites by analysis of variance (ANOVA) is presented in Table 3. Among the three categories of sites, distribution of Cd, Cr, and Pb was significantly (Table 3) higher ($p < 0.05$, Newman-Keuls) in mussels collected from IS.

Correlations of Metals

Correlation between concentrations of metals in whole tissue of *P. viridis* is given in Table 4. Pb correlated significantly with Cd and Cr ($p < 0.01$) while Cu showed strong correlation with Cr, Fe, Mn, Ni, and Zn ($p < 0.01$ and $p < 0.05$).

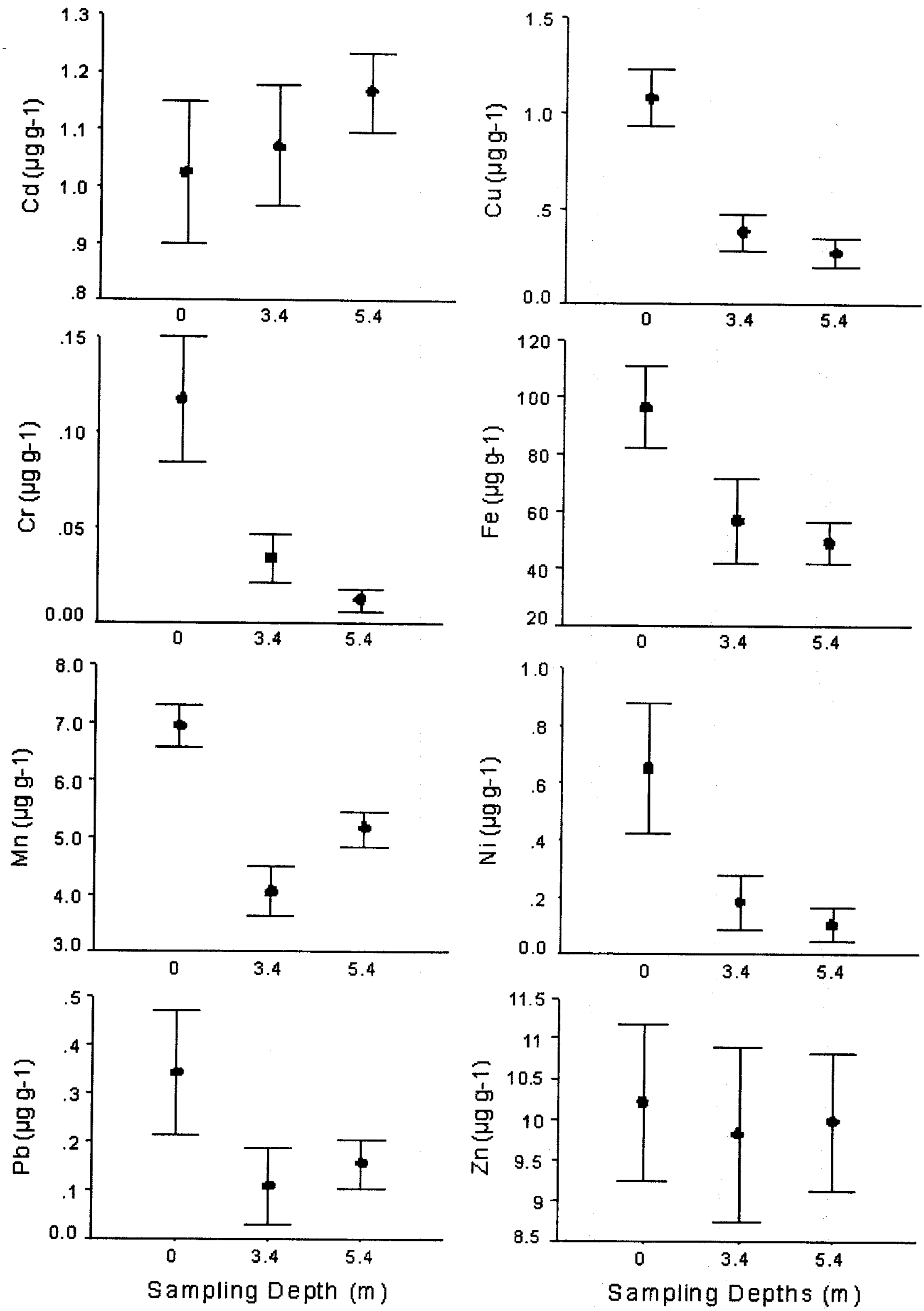

Fig. 2. Trace metal (mean + SD) concentrations (µg/g wet wt) in the whole tissue of natural populations of green mussel (*Perna viridis*) collected from three depths (intertidal: 0 m; subtidal: 3.4 m and 5.4 m) from the coastal waters of Karnataka

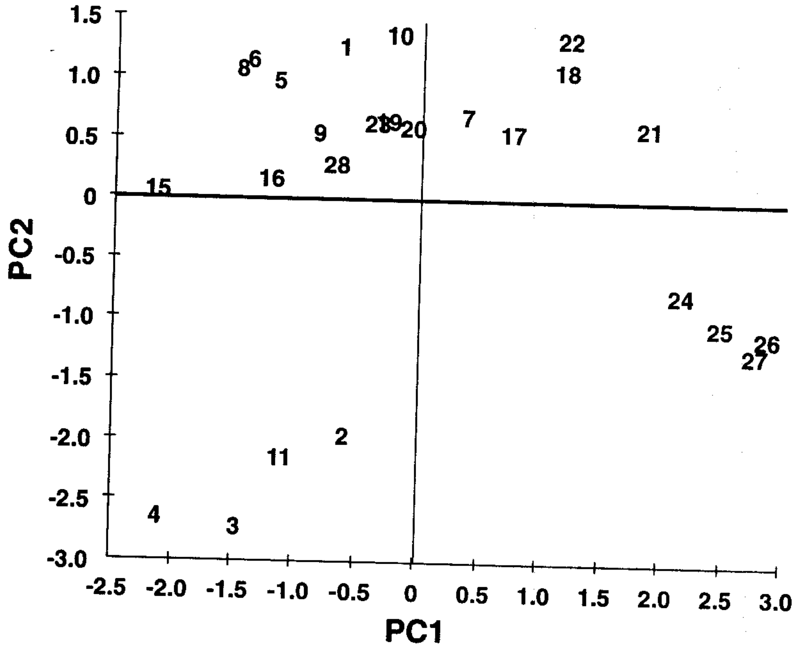

Fig. 3. Scatterplot of the sampling site scores (PCA) in space spanned by axis PC1 and PC2 of metal concentrations in green mussel (<80 mm). For site codes refer to Figure 1

Table 3. Mean concentrations of trace metals in the whole tissue (μg g^{-1} wet wt) of green mussel, *Perna viridis*, collected from industrial sites (IS), urban sites (US), and nonurban sites (NS) with intersite variability (ANOVA)

Site category	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
IS	$2.02^a \pm 1.41$	$0.33^a \pm 0.12$	$0.62^a \pm 0.43$	80.55 ± 33.56	$3.81^a \pm 1.53$	$0.50^a \pm 0.46$	$1.90^a \pm 0.07$	9.49 ± 1.12
US	$0.70^b \pm 0.48$	$0.17^b \pm 0.16$	$1.63^b \pm 0.31$	71.24 ± 58.88	$8.01^b \pm 1.59$	$1.26^b \pm 1.07$	0.00^b	10.36 ± 2.43
NS	$1.16^b \pm 0.53$	$0.012^c \pm 0.05$	$0.36^a \pm 0.54$	70.83 ± 77.16	$4.76^a \pm 2.30$	$0.02^c \pm 0.13$	$0.22^b \pm 0.49$	10.18 ± 6.98
All sites	1.18 ± 0.76	0.08 ± 0.14	0.60 ± 0.68	72.02 ± 70.23	5.18 ± 2.47	0.28 ± 0.65	0.38 ± 0.70	10.13 ± 6.00
F	11.22*	64.43*	36.71*	0.08	15.75*	42.16*	75.39*	0.07

* Significantly different groups marked ($p < 0.05$) with letters a, b, and c.

Table 4. Correlation between tissue concentrations of metals in *Perna viridis* from coastal waters of Karnataka ($p < 0.05$)

Cd	(+)Pb				
Cr	(+) Cu	(+) Fe	(+) Ni	(+) Pb	
Cu	(+) Cr	(+) Fe	(+) Mn	(+) Ni	(+) Zn
Fe	(+) Cr	(+) Cu	(+) Mn		
Mn	(+) Cu	(+) Fe	(+) Ni		
Ni	(+) Cr	(+) Cu	(+) Mn		
Pb	(+) Cd	(+) Cr			
Zn	(+) Cu				

(+) = positive correlation (−) = negative correlation.

Significant positive correlations ($p < 0.01$ and $p < 0.05$) were also observed between Zn and Cu.

Discussion

The mean tissue concentrations of toxic trace metals in *P. viridis* collected from 28 sampling sites along the Karnataka coast were found to be below the WHO permissible concentrations given for seafood (WHO 1972, 1987). The Cd levels in green mussels from industrial areas slightly exceeded the WHO permissible level for seafood (Table 3).

The variations in Cr, Cu, Fe, and Pb accumulation by mussels of different size groups were found statistically significant (Table 2). Statistically significant negative correlations were observed between mussel size and tissue concentrations of Cr, Cu, Fe, and Pb. Szefer *et al.* (2004) observed a similar negative correlation between trace metals such as Cr, Fe, Mn, Ni, Sn, and Ti levels and size in blue mussels. In the present study, Cu, Cr, Fe, and Pb concentrations were significantly higher in smaller mussels compared to larger mussels. Airas (2003) reported a similar negative trend for Cu in *M. edulis*. Such a relationship was also observed in *M. edulis* by Brix and Lyngby (1985) for Cr. According to Brix and Lyngby (1985) and Otchere (2003), the uptake of metals in bivalves was higher in smaller individuals than in larger ones generally resulting in a "growth dilution effect." In this way, while the metal burden would increase with age, concentration would diminish with the weight/size within each age class, if growth were more rapid than the accumulation rate. In the present study, no significant differences in Cd, Mn, Ni, and Zn concentrations were observed among different size groups. Riget *et al.* (1996) observed Zn to be independent of size.

In the present study, the Cr, Cu, Fe, Mn, and Ni showed significantly higher concentrations in intertidal mussels when compared to subtidal mussels between 3 m and 5 m deep (Fig. 2). No significant differences were found in concentrations of Cd, Pb, and Zn in mussels from intertidal beds compared to subtidal beds. However, the mean concentrations of Pb and Zn were high in intertidal mussels while concentrations of Cd were higher in subtidal mussels (Fig. 2). Phillips (1976a, b) recorded the highest values of Zn, Cd, and Pb levels in intertidal mussels collected at low saline waters. According to Schulz-Baldes (1974), blue mussels take up cadmium in dissolved form, while lead is taken up from food particles and from water in similar rates. A common feature of metal distributions is a general tendency for decreasing concentrations in the offshore directions. This feature is caused by a high concentration of heavy metals in land-based suspended matter supplied to the bay from surface run-off. Similar metal distribution was observed by Borg and Jonsson (1996) and Pempkowiak *et al.* (2005) in coastal areas.

The analysis of variance in tissue concentrations of Cd, Cr, Cu, Mn, Ni, and Pb was significantly different ($p < 0.01$) between the different categories of sites. Lead concentrations observed in *P. viridis* in the present study were 2–4 times lower than those reported by Krishnakumar *et al.* (1998) along the Karnataka coast. (It was below the detectable levels in tissues from the majority of sites from NS.) The observed decrease in bioaccumulation of lead in mussels may be due to the recent practice of using unleaded motor fuel.

To obtain homogeneous groups for metal accumulation in mussels, a range test (Newman–Keuls test) was performed, which revealed the presence of two homogeneous groups of sites, namely IS and other sites. Increased concentrations of Pb in mussels from IS were observed when compared to US and NS (Table 3). The samples from IS were taken from buoys kept afloat near the navigational channel of the major port, which receives input from industries including a refinery and dye and pigment manufacturing plant. In the IS, the industrial input of lead as well as that from fuel can produce such a marked effect. The importance of fuels as a source of lead in the marine environment is discussed by Phillips (1976a, b), which can cause a high concentration of tetra-ethyl lead in the vicinity of marinas. Fowler (2002) found higher levels of Pb in bivalves from areas subjected to substantial nonoil and oil industrial inputs in the Middle East. Szefer *et al.* (2004) attributed elevated levels of Pb and Cd accumulation in *Mytilus galloprovincialis* from Onsan Harbour, Korea, to shipping and industrial activities.

In the present study, Cd and Cr concentrations in mussels from IS were significantly higher when compared to other categories of sites (Table 3). A range test revealed two homogeneous subgroups for Cd bioaccumulation, the first comprising IS and the second comprising the other two categories (Table 3). When compared with earlier studies (Krishnakumar *et al.* 1998) from IS, the Cd concentrations recorded in the present study were three times higher. Mohankumar *et al.* (2003) observed as high as 14.90 μg/g of Cd and 177 μg/g of Cr in macrobenthos, consisting mainly of molluscs, from the industrial area off the Mangalore coast. In the present study, Cr was the least accumulated of the eight metals studied. Low levels of Cd were recorded in mussels collected from islands off Uttara Kannada district. Similar trends were reported by Krishnakumar *et al.* (1990) in *P. viridis* collected from Sungeri Island near Karwar.

High Fe levels were evident in all the sites and Fe accumulation was highest among the metals studied. Relatively consistent tissue concentrations of Zn were observed in mussels throughout the coast. There was no significant difference in the distribution of Zn in mussel tissues between the different categories of sites. Like Fe, Zn concentrations in the mussel were high and comparable with similar studies (Table 5) reported by Sankaranarayanan *et al.* (1976) and Krishnakumar *et al.* (1998) and relatively lower than those reported by other authors from Indian waters (Zingde *et al.* 1976; Rajendran *et al.* 1988; Senthilnathan *et al.* 1998; Radhakrishnan 1993; Tewari *et al.* 2000, 2001). The highest values for Zn were found in NS followed by IS. Krishnakumar *et al.* (1998) recorded Zn values as high as 72 $\mu g\ g^{-1}$ dry wt in the sediments from the coastal waters of Karnataka. Concentrations of the toxic trace metals in green mussels were clearly below the limit set by WHO for seafood (WHO, 1972, 1987).

Cu levels detected in the present study were comparable (Table 5) with earlier studies from nonurban sites of Karnataka; on the other hand, the Cu levels were lower when compared to industrial and urban sites of Karnataka (Krishnakumar *et al.* 1998) and those reported by other authors in Indian waters (Zingde *et al.* 1976; Rajendran *et al.* 1988; Senthilnathan *et al.* 1998; Radhakrishnan 1993; Tewari *et al.* 2000, 2001). Ni concentrations were below detectable levels in green mussels from a majority of the sampling stations along the coast. The data available on Ni and Cr concentrations in mussel tissue from this coast is scarce. However, the concentration of Ni recorded in the present study remained within the ranges previously reported from green mussel from Cochin and Calicut waters (Radhakrishnan 1993), though some authors have reported higher levels in green mussels from the coastal waters of Gujarat (Tewari *et al.* 2000, 2001).

A significant positive correlation of Cu ($p < 0.01$ and $p < 0.05$) with Cr, Fe, Mn, Ni, and Zn was observed (Table 4). Several authors have reported a correlation between Cu and Zn (Phillips 1976a, b; Riget *et al.* 1996). Phillips (1976a, b) found that the net uptake of copper by mussel was extremely erratic, and was affected by salinity, temperature changes, and by the presence of other metals and changes in their relative concentrations.

Tissue concentrations of metals observed in mussels in the present study were comparable with earlier studies reported in mussels from the west coast of India (Table 5). Variations in trace metal bioaccumulation being evident within size groups and among exposed and submerged populations, size and depth of sampling ought to be considered in mussel watch

Table 5. Metal concentrations (μg/g tissue weight) reported in green mussel *Perna viridis* from the west coast of India

Locations	Cd	Cu	Fe	Mn	Ni	Pb	Zn	Reference
Cochin backwaters[a]		22.26 ± 5.5	374.6 ± 257.7			7.59 ± 1.27	79.18 ± 12.14	Lakshmanan and Nambisan (1983)
Karwar[b]	0.31 ± 0.08	1.50 ± 0.50		6.80 ± 0.76		0.33 ± 0.10	14.39 ± 0.47	
Majali[b]	0.16 ± 0.02	1.77 ± 0.21		5.24 ± 0.33		0.31 ± 0.03	11.06 ± 0.23	
Sungeri Is.[b]	0.15 ± 0.03	0.86 ± 0.19		3.62 ± 0.69		0.32 ± 0.03	11.09 ± 1.11	
Devgad Is.[b]	0.34 ± 0.08	2.25 ± 0.32		6.98 ± 0.14		0.50 ± 0.07	14.54 ± 0.52	Krishnakumar *et al.* (1990)
Arga[b]	0.22 ± 0.08	1.57 ± 0.63		8.86 ± 0.20		0.80 ± 0.08	13.97 ± 2.89	
Amdalli[b]	0.28 ± 0.04	2.89 ± 0.67		6.18 ± 0.74		0.22 ± 0.06	13.93 ± 0.25	
Harwada[b]	0.24 ± 0.03	2.62 ± 0.19		8.10 ± 0.73		1.03 ± 0.42	14.16 ± 1.10	
Belekeri[b]	0.12 ± 0.06	1.86 ± 0.21		6.67 ± 0.24		0.26 ± 0.03	11.62 ± 0.98	
Karnataka Majali[b]	0.16	1.8				0.31	11.1	
Karwar[b]	0.31	1.5				0.33	14.4	
Argae[b]	0.22	1.57				0.8	14	Krishnakumar *et al.* (1998)
Kaup[b]	0.54	17.1				1.48	23.3	
Surathkal[b]	0.71	23.6				1.8	49.7	
Thaneerbhavi[b]	0.81	128				2.52	70.5	
Gujarat Mocha[a]	1.53	3.91	9.40	1.01		20.10	37.34	Tewari *et al.* (2000)
Gujarat Mocha[a]	4.2–1.08	6.82–21.22	230.6–302.3	5.25–16.28	19.5–53.15	30.56–63.84	40.23–82.8	Tewari *et al.* (2001)
Dwaraka[a]	2.54–9.48	14.24–40.47	389.4–618.3	12.52–29.54	32.81–65.45	45.28–92.38	52.62–813.28	
Calicut & Cochin[a]	2.5	7.34	16.28	0.33	2.25	6.12	344.52	Radhakrishnan 1993
Karnataka Coast[b]	0.03–3.71	nd–2.3	nd–285.4	nd–11.41	nd–3.5	nd–2.00	nd–34.1	Present study

[a] Dry wt.
[b] Wet wt.

programmes. Generally, the levels of toxic trace metals like Pb, Cd, Ni, and Cr in the whole tissue of *P. viridis* were low throughout the coast of Karnataka and within the safe limits. However, relatively high concentrations of Cd, Cr, and Pb were observed in the whole tissue of green mussels collected from the coastal waters adjacent to the industrial areas near Mangalore (southern tip of Karnataka), which may be derived from a variety of anthropogenic activities. The trace metal concentrations in the coastal environment of the Karnataka coast need to be monitored on a regular basis due to the rapid increase in industrialization of the area.

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