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COMPARISON OF PCB AND TRACE METAL BIOACCUMULATION IN THE BLUE MUSSEL, *MYTILUS EDULIS*, AND THE RIBBED MUSSEL, *MODIOLUS DEMISSUS*, IN NEW BEDFORD HARBOR, MASSACHUSETTS

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Abstract—The accumulation of PCBs and trace metals was compared at 14-d intervals between two filter-feeding bivalves, the blue mussel, *Mytilus edulis*, and the ribbed mussel, *Modiolus demissus*, after deployment in New Bedford Harbor, Massachusetts, for up to 56 d. Contaminant uptake in deployed organisms also was compared with indigenous ribbed mussels. Significant mortality (>80%) occurred in blue mussels after 28 d, when water temperatures exceeded 25°C. Therefore, tissue-residue comparisons between species are presented only up to day 28, while those between deployed and indigenous ribbed mussels continue to day 56. Results indicated that total PCB tissue residues and congener distributions were not statistically different ($p > 0.05$) in the two mussel species on day 28. Total PCB concentrations in both deployed mussel species reached approximately 30 $\mu g\ g^{-1}$ dry weight by day 28. Additionally, total PCB concentrations and congener distributions in the deployed ribbed mussels were not statistically different from the indigenous ribbed mussels on day 28, demonstrating that steady state was attained within 28 d. With respect to metal uptake, no single accumulation pattern occurred for the eight metals quantified. After 28 d, lead, cadmium, and iron concentrations in deployed blue and ribbed mussels were statistically similar. However, nickel and zinc accumulations were significantly greater in the blue mussels, and copper, chromium, and manganese were accumulated to significantly higher concentrations in the ribbed mussels. The comparison between the ribbed mussels indicated that cadmium and lead concentrations were significantly higher in indigenous than in deployed mussels after 28 d.

Keywords—Bioaccumulation *Mytilus edulis* *Modiolus demissus* PCBs Metals

INTRODUCTION

The use of bivalves to measure the levels of bioavailable contaminants has been established in numerous monitoring and research programs [1-9]. Mussels have been shown to bioconcentrate many organic and inorganic contaminants by factors of 10^2 to 10^5 above ambient seawater concentrations [10], thus providing a direct representation of pollutant bioavailability in a time-integrated fashion [11]. This approach eliminates the need for repetitive single-point measurements of pollutants in the ambient seawater.

Tissue residues in these sentinel organisms have been used to identify contaminated marine habitats, especially in coastal areas [10,12]. Monitoring programs such as the U.S. Environmental Protection Agency's (EPA's) Mussel Watch [5], National Oceanic and Atmospheric Administration's (NOAA's) National Status and Trends Program (NS&T) [13], and EPA's Environmental Research Laboratory, Narragansett (ERL-N), Rhode Island, Coastal Environmental Assessment Program [14] have utilized the blue mussel, *Mytilus edulis*, as a marine monitoring organism. Although several of these studies have employed indigenous organisms, deployed (i.e., transplanted for a finite time period) organisms have been used to monitor pollutant concentrations in areas where no indigenous population existed [4,9,15].

Because of physiological limitations, however, the use of the blue mussel as an indicator or sentinel organism is limited in areas of higher water temperatures (i.e., excessive stress or mortality occurs when the temperature tolerance is exceeded). Therefore, it would be beneficial to identify other bivalve species for monitoring areas where the temperature tolerance of the blue mussel is exceeded, while retaining such beneficial characteristics as widespread distribution and the ability to accumulate contaminants. Although oysters (*Crassostrea virginica* and *Ostrea sandvicensis*) and other mussel species (*Mytilus californianus*) have been employed in the Mussel Watch and NS&T programs, their utility as sentinel organisms is diminished slightly by their narrower geographical distributions compared to the blue mussel. Another candidate species, the ribbed mussel (*Modiolus demissus*) is more eurythermal than the blue mussel [16] while still maintaining a wide geographical distribution. These advantageous characteristics would allow ribbed mussels to supplement monitoring programs in areas where blue mussels would not survive. Despite these advantages, there are relatively few literature references on the use of ribbed mussels in marine monitoring [17,18].

The current study focuses on the potential of the ribbed mussel *M. demissus* as an indicator organism for monitoring contaminant bioaccumulation. The approach taken was to compare bioaccumulation in the ribbed mussel to that of the blue mussel, a species previously documented as an ef-

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fective monitoring organism. The bioaccumulations, as well as mortality, of PCBs and eight metals were determined in both mussel species deployed up to 56 d in New Bedford Harbor, Massachusetts. In addition, contaminant levels in deployed ribbed mussels were compared to those of an indigenous population to ascertain the time frame for steady state to be achieved in the deployed mussels. New Bedford Harbor (NBH) was selected as the deployment site for three reasons: (a) Previous studies at this site revealed that sediments and overlying seawater were heavily contaminated with both organic (e.g., sediment PCB concentrations up to 100,000 $\mu g\ g^{-1}$) and inorganic compounds; (b) prior blue mussel deployments in NBH had shown that PCBs were accumulated to 35 to 60 $\mu g\ g^{-1}$ in 28 d; and (c) indigenous ribbed mussels were available for comparison with the deployed mussels.

MATERIALS AND METHODS

Sample collection

Blue mussel (*Mytilus edulis*) collection and deployment procedures are detailed in Bergen et al. [19]. Briefly, blue mussels were collected from a clean reference area in East Sandwich, Massachusetts, and sorted to include organisms 5 to 7 cm in length. Twenty-five mussels were placed into polyethylene baskets for deployment in New Bedford Harbor at the Coggeshall Street Bridge, the southern boundary of the severely PCB-contaminated upper harbor. Deployments began at the end of June and were completed by the end of August 1991. Baskets were deployed at four substations: two on the north side and two on the south side of the Coggeshall Street Bridge. Each substation consisted of baskets of mussels suspended 1 m above the bottom. Separate baskets were used for each deployment length (i.e., days 14, 28, 42, and 56). On each sampling date, mussels were collected from each substation and returned to the laboratory on ice. After quantifying mortality, mussels were placed in Ziploc® bags and frozen at −20°C. Three of the replicates from each deployment period were analyzed; the fourth was archived.

Ribbed mussels (*Modiolus demissus*) were collected from a clean reference location on West Island in Buzzards Bay, Massachusetts. Following sorting to 5 to 7 cm length, 25 organisms were placed into baskets, similar to those used for the blue mussels. These baskets were deployed side-by-side with the baskets containing the blue mussels at each substation. Retrieval procedures were identical to those used for the blue mussels.

Indigenous ribbed mussels were collected on days 28, 42, and 56 from intertidal rocks at the Coggeshall Street Bridge. Twenty-five mussels were collected on each date and pooled into one sample. These mussels were placed in Ziploc bags, returned to the laboratory on ice with the deployed mussels, and frozen at −20°C until analysis.

Organic sample extraction

Mussel samples (both ribbed and blue) were analyzed following a method modified from Bergen et al. [19]. The frozen mussels were shucked and the soft tissue homogenized using a Polytron® (Brinkmann Instruments, Westbury, NY) equipped with titanium blades. One gram of each homogenate was dried overnight at 120°C for wet-to-dry weight ratio determinations. Approximately 1 to 2 g of homogenate was weighed into a solvent-rinsed 100-ml glass centrifuge tube. The PCB congener 198 (2,2′3,3′,4,5,5′,6-octachlorobiphenyl) was added as an internal (also known as a surrogate) standard, and the samples were extracted with 25 ml of acetone by grinding with the Polytron for 20 s. Following centrifugation, the supernatant was poured into a 1-L separatory funnel containing 300 ml of freon-rinsed deionized water. The extractions were repeated twice and the extracts combined in a separatory funnel where they were extracted 3 times with freon (25 ml each time). Sodium sulfate was added to the combined freon extracts to remove water, and the volume of the extracts was reduced under nitrogen and exchanged to 10 ml of hexane. One milliliter of the extract was removed for gravimetric total lipid determination, while the remaining 9 ml were reacted with concentrated sulfuric acid to remove organic interferences. The sample was removed from the acid by Pasteur pipette, reduced in volume, exchanged to 1 ml of heptane, and transferred to a borosilicate screw-top vial for storage until analysis.

Organic sample analysis

The heptane extracts were analyzed for individual PCB congeners by electron-capture–gas chromatography (GC-EC). Automated splitless-mode injections of 1 μl were made into a Hewlett–Packard 5890 gas chromatograph equipped with a 30-m DB-5 fused silica capillary column and an electron-capture detector. Injection port temperature was maintained at 275°C, and detector temperature was 325°C. Initial column temperature was 100°C, with a 1-min hold time, and then was increased to 140°C at 5°C min^{-1} and held for 1 min. The oven temperature was increased to 230°C at 1.5°C min^{-1} and held at that temperature for 20 min. Finally, oven temperature was increased at 10°C min^{-1} to 300°C and held for 5 min. Total run time was 100 min. Access*Chromo© software from Perkin–Elmer Nelson Systems was used to analyze the raw data. A total of 18 individual congeners (Table 1) were quantitated against the internal standard in each mussel sample. These congeners, encompassing dichloro- through decachlorobiphenyl, are the same ones measured by the NS&T Program. Total PCB concentrations were obtained as the summation of the 18 congeners. Multiple-level calibration standards were analyzed to generate the calibration curves used to obtain sample analyte concentrations.

Metal sample preparation

A 15-g portion of each mussel homogenate was freeze-dried, placed in a digestion vessel, and 15 ml of concentrated nitric acid was added. Microwave heating was used to digest the samples. A three-step open vessel digestion was followed by a three-step closed vessel digestion with 3 ml of hydrogen peroxide per sample. Power settings for each digestion were adjusted according to the number of samples being processed. Following digestion, samples were filtered through Whatman no. 42 filter paper with deionized water rinses. The volume of the combined filtrates was adjusted to 50 ml in a

Table 1. Organic and inorganic analytes quantified in deployed and indigenous mussel (*Mytilus edulis*, *Modiolis demissus*) samples from New Bedford Harbor, Massachusetts

PCBs		Inorganic elements
Congener[a]	Substitution pattern	
CB008	2,4′-dichlorobiphenyl	Cadmium
CB018	2,2′,5-trichlorobiphenyl	Copper
CB028	2,4,4′-trichlorobiphenyl	Zinc
CB052	2,2′,5,5′-tetrachlorobiphenyl	Lead
CB044	2,2′,3,5′-tetrachlorobiphenyl	Nickel
CB066	2,3′,4,4′-tetrachlorobiphenyl	Chromium
CB101	2,2′,4,5,5′-pentachlorobiphenyl	Manganese
CB118	2,3′,4,4′,5-pentachlorobiphenyl	Iron
CB153	2,2′,4,4′,5,5′-hexachlorobiphenyl	
CB105	2,3,3′,4,4′-pentachlorobiphenyl	
CB138	2,2′,3,4,4′,5′-hexachlorobiphenyl	
CB187	2,2′,3,4′,5,5′,6-heptachlorobiphenyl	
CB128	2,2′,3,3′,4,4′-hexachlorobiphenyl	
CB180	2,2′,3,4,4′,5,5′-heptachlorobiphenyl	
CB170	2,2′,3,3′,4,4′,5-heptachlorobiphenyl	
CB195	2,2′,3,3′,4,4′,5,6-octachlorobiphenyl	
CB206	2,2′,3,3′,4,4′,5,5′,6-nonachlorobiphenyl	
CB209	Decachlorobiphenyl	

[a]PCB congener numbers correspond to the numbering system of Ballschmiter and Zell [33].

volumetric flask, and the sample were stored in 60 ml polyethylene bottles until analysis.

Metal sample analysis

Samples were analyzed by inductively coupled plasma atomic emission spectrometer (ICP) for Cu, Cd, Pb, Cr, Ni, Zn, Fe, and Mn. Multiple-level calibration standards were analyzed to generate calibration curves against which sample concentrations were calculated.

Quality assurance/quality control (QA/QC) activities

Several QA/QC procedures were employed to ensure the validity of the analytical data. Procedural blanks were analyzed with each sample batch; all were found to be free of interferences that could affect the measurement of the analytes of interest. Certified reference materials were analyzed with a frequency of 5% to assess analytical accuracy. The recoveries, based on the percentage of the certified value, were generally 75 to 125% for the PCBs and 85 to 115% for the metals. To assess analytical precision, approximately 5% of the samples were analyzed in triplicate. Generally, the coefficients of variation were less than 10% for each analyte of interest.

Statistical analyses

Statistical analyses were completed using programs from the Statistical Analysis System (SAS) Institute [20]. Statistical differences were determined at the 95% confidence interval for mortality and the PCB and trace metal measurements using a Student's *t* test. Tissue-residue concentrations in indigenous ribbed mussels collected on days 28, 42, and 56 from NBH-2 were quantified on one pooled sample of approximately 25 organisms per sampling date. Tests of statistical differences in tissue residues between deployed and indigenous ribbed mussels on days 28, 42, and 56 were completed using the *t* test for comparison of a single observation (indigenous mussels) with the mean of a sample (deployed mussels ($p = 0.05$) [21].

RESULTS AND DISCUSSION

Mortality

Significant differences ($p < 0.05$) in mortality were observed between the two species on days 28, 42, and 56 (Table 2). Although mortality in the ribbed mussels never exceeded 10% throughout the 56-d deployment interval, mortality in the blue mussels increased from less than 5% after 14 d to a mean of 80% after the 56-d deployment.

Observed differences in mortality were probably due to differences in thermal tolerances between the two mussel species and ambient temperatures during the deployment period. Although continuous temperature data were not collected, periodic measurements indicated that water temperatures reached 27°C by the end of the deployment. Lethal temperatures of 25 to 27°C have been reported for the blue mussel and 35 to 40°C for the ribbed mussel [16]. Therefore, the blue mussels were adversely impacted by the elevated water temperatures whereas survival of the deployed ribbed mussel population was not affected. Previous blue mussel deployments at this site, conducted during other parts of the year when water temperatures were lower, resulted in much lower mortality rates (<10%) through a 28-d deployment. Because of the excessive mortality after day 28 in the blue mussel, tissue-residue data for days 42 and 56 may not be representative of normal conditions. Therefore, only blue mussel tissue-residue data up to and including day 28 will be presented here.

PCB concentrations

Total PCB concentrations, as the summation of the 18 measured congeners (Table 1), for each mussel species are presented in Figure 1. A significant difference ($p < 0.05$) was found between the day 0 total PCB concentrations in the two species, indicative of the different collection sites, and this was still apparent on day 14. However, both species continued to accumulate PCBs, and by day 28 the total PCB con-

Table 2. Cumulative percent mortality (SD) in blue (*Mytilus edulis*) and ribbed (*Modiolus demissus*) mussels at 14-d intervals of a 56-d deployment in New Bedford, Massachusetts

	% Mortality (SD)			
Mussel	Day 7	Day 28	Day 42	Day 56
Blue	5 (3.8)	17 (6.8)	68 (12)	80 (6.9)
Ribbed	1 (2)	2 (2.3)	5.3 (6.1)	11 (6.1)

Four replicates were collected for each species on each date, except for day 28 when only three replicates were recovered. Mortality was significantly greater ($p < 0.05$) in blue mussels on days 14, 28, 42, and 56.

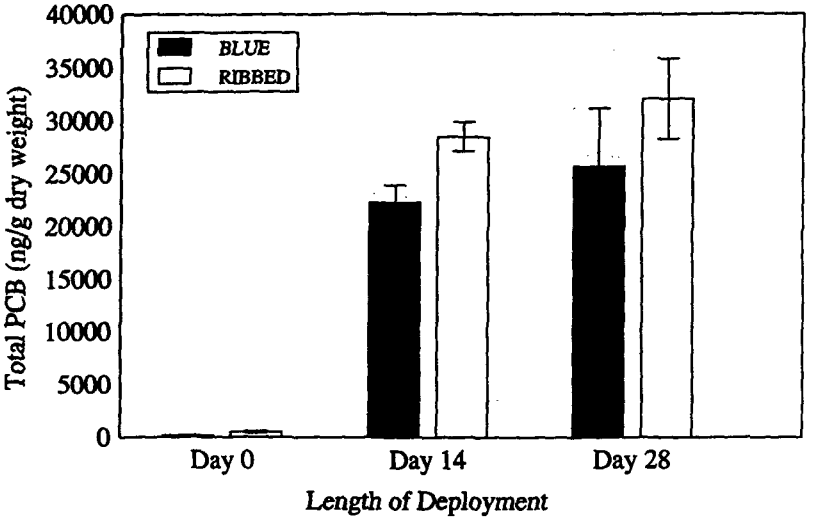

Fig. 1. Total PCB concentrations (as the sum of the 18 measured congeners) in blue and ribbed mussels deployed in New Bedford Harbor. Concentrations are reported in ng g^{-1} on a dry-weight basis. Error bars represent 1 SD from the mean.

centrations in the blue and ribbed mussels were not statistically different ($p > 0.05$).

With respect to the individual 18 PCB congeners measured in each species, 65% were significantly different in the day 0 mussels, again reflecting the different collection sites (Fig. 2a). However, by day 14, significant differences were apparent for only 12% of the congeners (Fig. 2b), and on day 28 (Fig. 2c) no significant differences were observed in the PCB congener concentrations measured in the two species. These data indicate that both mussel species accumulated comparable PCB congener concentrations within 28 d. The results presented here are consistent with several other studies. Tavares et al. [22] found similar PCB congener concentrations in eight indigenous marine bivalve species in Brazil. Muncaster et al. [23] deployed two species of freshwater bivalves at four sites in Canada and observed no significant differences in PCB uptake between species after 40 d.

Comparison of the total PCB concentrations between deployed and indigenous ribbed mussels indicated no statistical difference on day 28 (Fig. 3). Likewise, the individual PCB congeners measured in deployed and indigenous ribbed mussels indicated no significant difference on day 28 (Fig 4a). These observations are similar to other studies that have documented that steady-state concentrations have been attained in mussels after a 28-d exposure period [3,19,24].

After day 28, the PCB concentrations in the deployed and indigenous mussels decreased (Fig. 3). Total PCB concentrations were lower on day 42 in both deployed and indigenous ribbed mussels and remained lower on day 56, although not significantly different on either date. However, on days 42 (Fig. 4b) and 56 (Fig. 4c), 35% and 24%, respectively, of the individual congeners were significantly different. While the differences in various individual congener concentrations were statistically significant, the measured congener concentrations generally varied by less than 20%. These data indicate that the PCB concentrations in the deployed ribbed mussels closely followed those in the indigenous ribbed mussels over the entire deployment period of 56 d.

The most probable explanation for the decrease in PCB concentrations in both the indigenous and deployed ribbed mussels after day 28 would be spawning in these organisms. However, direct evidence of spawning in this study, as quantified by a significant decrease in lipid weight, was not observed. Gravimetric lipid weight determinations made on all samples in the current study indicated no significant change in the lipid weight for either deployed species or the indigenous population over the deployment period. For this reason, PCB data collected during this study were not normalized for lipid content. It is possible that this finding is due either to a lack of sensitivity in the method used to quantify lipids or that spawning was not complete.

Nevertheless, previous studies indicate that at least partial spawning could be expected at this time of the year in these mussels. Bayne [16] indicated that spawning in this species occurred generally between May and September, with a peak period in August. This time frame wholly encompassed the deployment period, which began in late June and terminated in late August. Capuzzo et al. [25] noted that a decline in chlorobiphenyl congener concentrations in blue mussels in nearby Buzzards Bay was correlated to spawning activity. That study found that PCB concentrations fluctuated during the late spring and early summer and that a marked decline occurred during the autumn. Their observed variability in spawning patterns could explain differences observed in this study in the concentration of several congeners on days 42 and 56 between the deployed mussels collected from West Island and the indigenous ribbed mussels from upper NBH.

The tissue-residue data for the blue and ribbed mussels demonstrate that both species accumulated significant (relative to day 0) and statistically comparable total PCB concentrations and congener distributions within 28 d. Additionally, the comparison of deployed and indigenous ribbed mussels

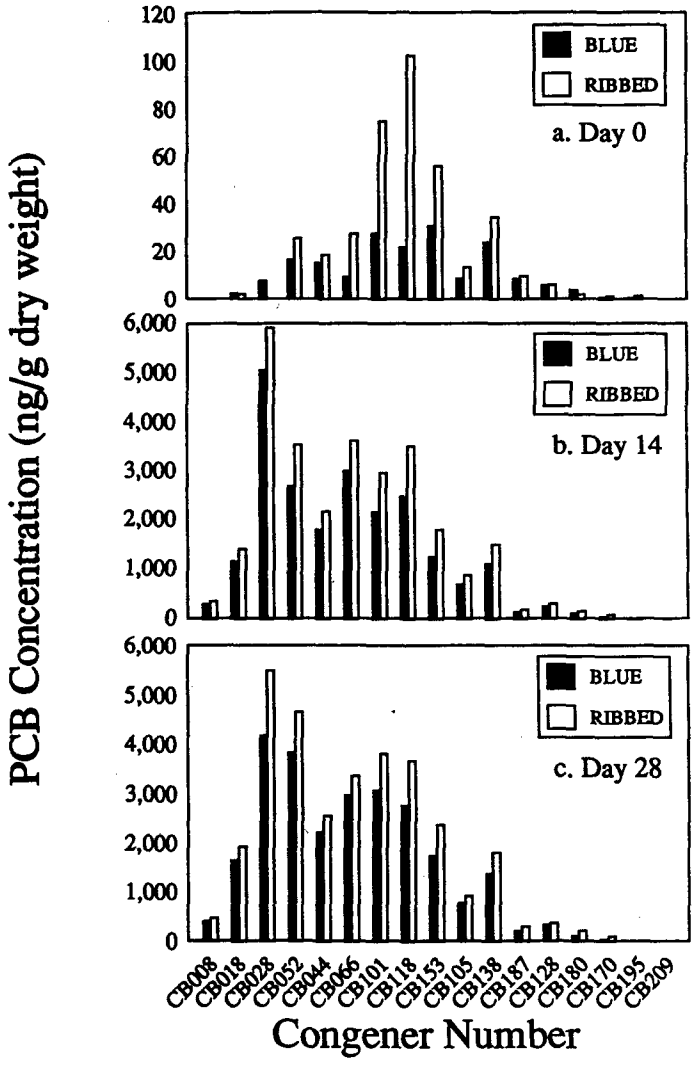

Fig. 2. Individual PCB congener concentrations in blue and ribbed mussels deployed in New Bedford Harbor. Concentrations are shown for days 0 (a), 14 (b), and 28 (c) and are reported in ng g^{-1} on a dry-weight basis. Note scale change between day 0 and days 14 and 28 PCB concentrations.

indicated that a steady-state condition was attained within this time. This time frame for reaching steady-state PCB accumulation in blue mussels is consistent with the findings reported by Bergen et al. [19] under field conditions and Pruell et al. [3] for a laboratory exposure. The higher temperature tolerance of the ribbed mussel resulted in minimal mortality throughout the 56-d deployment period, whereas significant mortality occurred in deployed blue mussels after 28 d when ambient temperatures exceeded 25°C. Together, these results demonstrate that deployed ribbed mussels are (a) an effective organism for monitoring selected PCB congener bioaccumulation in heavily contaminated marine areas, (b) directly comparable to the blue mussel with respect to PCB bioaccumulation, (c) especially suited for monitoring areas where elevated water temperature precludes using blue mussels, and (d) comparable to indigenous organisms with respect to PCB bioaccumulation.

Metals concentrations

Unlike the PCB congeners, which accumulated significantly and similarly in the deployed blue and ribbed mussels, tissue-residue concentrations for the eight metals quantified did not exhibit a uniform pattern of uptake between the two species. Four patterns emerged in metals accumulation after 28 d: (a) no significant accumulation in either species (Fe); (b) significant accumulation (relative to day 0) in only the blue (Cd) or the ribbed (Cr) mussels; (c) significant and similar accumulation in both species (Pb); and (d) accumulation in both species, though metals accumulation was significantly higher in the blue (Zn, Ni) or ribbed (Cu, Mn) mussels (Table 3).

The interspecies differences in metal tissue-residue concentrations observed in this study are not wholly unexpected based on other reported literature. Previous studies have at-

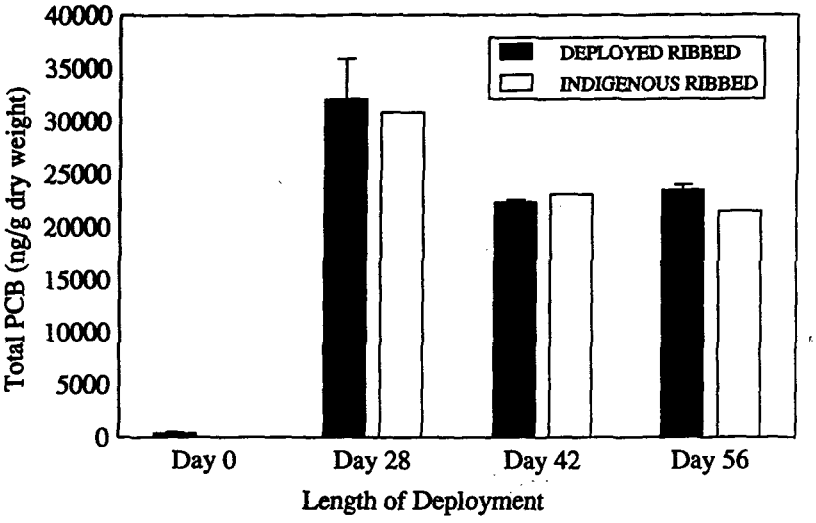

Fig. 3. Total PCB concentrations (as the sum of the 18 measured congeners) in deployed and indigenous ribbed mussels from New Bedford Harbor. Concentrations are reported in ng g^{-1} on a dry-weight basis and were single-point measurements for indigeneous mussels, collected on days 28, 42, and 56 only. Error bars represent 1 SD from the mean.

tributed differences in metal uptake in bivalves to a number of factors including organism size [26,27], previous exposure conditions [28], and genetic background [29,30]. In addition, within the same organism both differential uptake and depuration occur among various tissues [28,31,32]. Collectively, these findings highlight the fact that metal uptake in bivalves is a complicated process that can be affected by many exogenous and endogenous factors.

In the present study, several of these factors were controlled for as much as possible under field conditions. Similar-length mussels from clean areas were deployed at the same location under identical environmental conditions (i.e., temperature, salinity, food availability). Despite these efforts, metal accumulation in the two mussel species was different (Table 3). One obvious explanation for these findings is genetic variability. A study by Frazier and George [29] investigated Cd uptake in two oyster species, *Crassostrea gigas* and *Ostrea edulis*. Under controlled laboratory conditions, they found that *C. gigas* accumulated approximately three times as much Cd as *O. edulis* after 28 d. They attributed these results to different metal-binding protein synthesis capabilities between species. Likewise, Langston et al. [30] found

Table 3. Mean (SD) metal concentrations (μg/g dry wt.) on days 0 and 28 in blue (*Mytilus edulis*) and ribbed mussels (*Modiolus demissus*) deployed in New Bedford, Massachusetts

Metal	Mussel	Concn. (μg/g dry wt.) Day 0	Concn. (μg/g dry wt.) Day 28	Concentration factor
Iron	Blue	328 (57.6)	240 (33.0)	–
	Ribbed	202 (108)	267 (38.7)	–
Cadmium	Blue	0.72 (0.14)	1.03 (0.09) B	1.4
	Ribbed	1.08 (0.10)	1.18 (0.05)	–
Chromium	Blue	0.96 (0.34)	1.92 (0.54)	–
	Ribbed	0.54 (0.03)	3.26 (0.52) A,B	6.0
Lead	Blue	0.66 (1.14)	5.00 (0.42) B	7.5
	Ribbed	0.62 (0.54)	5.56 (0.64) B	9.0
Zinc	Blue	58.7 (7.22) A	120 (15.7) A,B	2.0
	Ribbed	34.0 (10.1)	52.8 (1.97) B	1.5
Nickel	Blue	0.24 (0.41)	1.58 (0.31) A,B	6.8
	Ribbed	0.14 (0.12)	0.54 (0.19) B	3.9
Copper	Blue	4.06 (0.91)	10.2 (1.70) B	2.5
	Ribbed	7.73 (1.42) A	22.0 (2.31) A,B	2.8
Manganese	Blue	8.10 (1.50)	11.9 (0.84) B	1.5
	Ribbed	7.92 (2.22)	16.2 (2.16) A,B	2.0

Significantly higher ($p < 0.05$) metal concentrations between each species on a given date (A) and between days 0 and 28 (B). When significant accumulation occurred between days 0 and 28, the corresponding concentration factor (day 28/day 0) is shown.

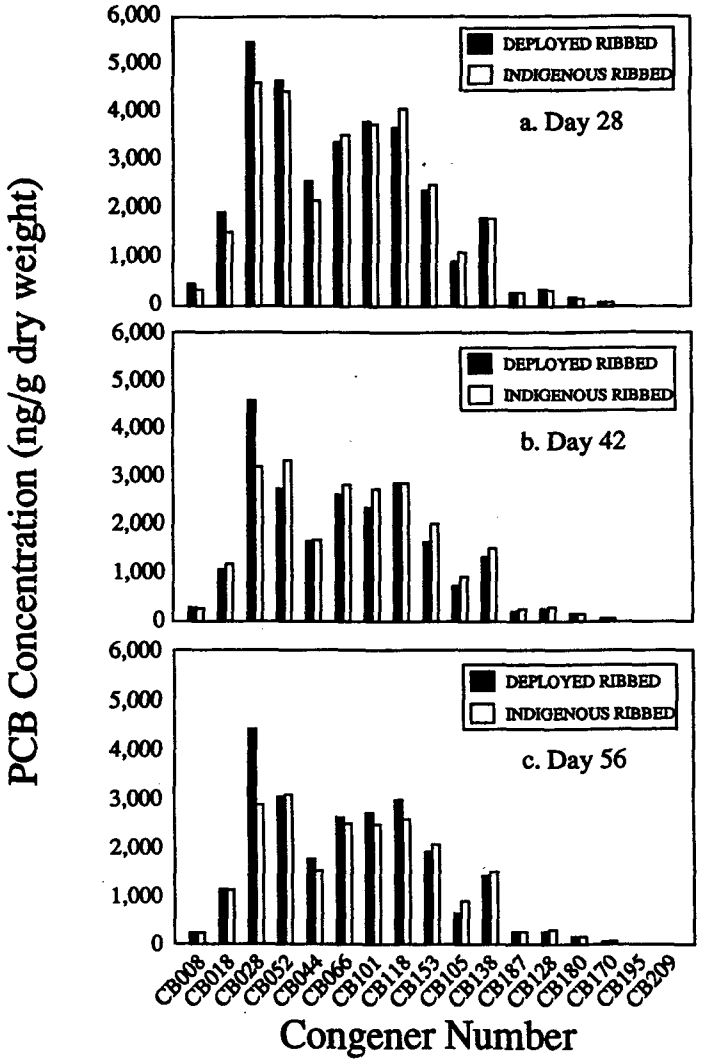

Fig. 4. Individual PCB congener concentrations in deployed and indigeneous ribbed mussels from New Bedford Harbor. Concentrations are shown for days 28 (a), 42 (b), and 56 (c) and are reported as ng g^{-1} on a dry-weight basis.

that variations in metallothionein-like proteins accounted for interspecific differences in Cd accumulation among three marine molluscs, *Mytilus edulis, Macoma balthica*, and *Littorina littorea*. It is probable that interspecies variability contributed to the differential uptake of some metals in the present study as well.

In addition to interspecies differences, intraspecific comparisons were made for metal uptake between deployed and indigenous ribbed mussels. Significantly higher concentrations of Cd and Pb were observed after 28 d in the indigenous mussels, relative to the deployed ribbed mussels (Table 4). Lead concentration in the indigenous ribbed mussel sample was a factor of three greater than the concentration measured in the deployed ribbed mussels. Similarly, the level of Cd in the indigenous samples was approximately two times greater than that of the deployed ribbed mussel samples. One explanation for these elevated concentrations in indigenous ribbed mussels is that the deployed mussels may not have had adequate time to reach steady state. Ritz et al. [28] found that Pb accumulated linearly with the period of exposure over 86 d. A second consideration is the previous exposure history of an organism. Ritz et al. [28] reported differential uptake in *Mytilus edulis planulatus* collected from two different locations after laboratory exposures to Cd and Pb. Intraspecific differences were observed also by Frazier and George [29]. *Ostrea edulis* collected from an uncontaminated site accumulated Cd faster than did the same species from a metal-contaminated site. Results of these studies strongly indicate that bioaccumulation of some metals by bivalves could be population dependent.

The purpose of quantifying metal accumulation in this study was to determine how comparable ribbed mussels are to blue mussels for monitoring contaminant bioaccumulation in the marine environment, not to identify the causes of any differences. The cited literature shows that many factors contribute to metal uptake, not only between species but also

Table 4. Comparison of the mean (SD) metal concentrations (μg/g dry wt.) for ribbed mussels (*Modiolus demissus*) from New Bedford Harbor, Massachusetts

Metal	Mussel type	Metal concn. (μg/g dry wt.) Day 0	Day 14	Day 28
Fe	Deployed	202 (13.4)	271.5 (72.5)	267 (38.7)
	Indigenous			198
Cd	Deployed	1.08 (0.02)	1.09 (0.03)	1.12 (0.05) *
	Indigenous			2.45
Cr	Deployed	0.54 (0.02)	2.59 (0.37)	3.26 (0.53)
	Indigenous			1.94
Pb	Deployed	0.62 (0.15)	4.43 (0.04)	5.57 (0.64) *
	Indigenous			15.0
Zn	Deployed	34.0 (0.49)	52.9 (2.22)	52.8 (1.97)
	Indigenous			50.5
Ni	Deployed	0.14 (0.06)	0.17 (0.13)	0.54 (0.20)
	Indigenous			0.25
Cu	Deployed	7.73 (0.86)	23.1 (6.20)	22.0 (2.31)
	Indigenous			15.3
Mn	Deployed	7.92 (0.40)	11.9 (0.74)	16.2 (2.16)
	Indigenous			11.9

Asterisks denote that day-28 deployed concentrations were statistically different from indigenous concentrations using a t test for comparison of a single observation (indigenous mussels) with the mean of a sample (deployed mussels) ($p = 0.05$) [21].

within a species. Based on this information and the data generated here, it is evident that great care must be exercised in the design and subsequent data interpretation of any application in which bivalves are used to monitor metal bioaccumulation in the marine environment.

This study highlights the potential use of the ribbed mussel as a deployed sentinel organism for measuring the bioaccumulation of PCBs. The effectiveness of the ribbed mussel as a useful biomonitor for measuring metals is less certain. Additional research to compare the bioaccumulation of other semivolatile organic compounds, such as chlorinated pesticides and PAHs, would provide a further assessment of the biomonitoring capabilities of this species. In addition, experiments should be conducted in other locations to determine whether accumulation between species is comparable at lower contaminant concentrations. However, given its widespread geographical distribution, wide temperature and salinity tolerances, and similarity in PCB bioaccumulation rates to the blue mussel, it appears that the ribbed mussel could expand the use of deployed mussels into areas outside of the physiological limits of the blue mussel.

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