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Trophic accumulation and depuration of mercury by blue crabs (*Callinectes sapidus*) and pink shrimp (*Penaeus duorarum*)

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Abstract

Mercury concentrations in blue crabs (*Callinectes sapidus*) collected from an area of mercury-contaminated sediments in Lavaca Bay, TX, USA, are more than an order of magnitude greater than concentrations in penaeid shrimp from the same area. Laboratory feeding experiments using mercury-contaminated fish as food showed that both blue crabs and pink shrimp (*Penaeus duorarum*) could accumulate mercury concentrations comparable to those in their food in 28 days. Calculated mercury assimilation efficiencies averaged 76% for blue crabs and 72% for pink shrimp. Significant depuration of mercury by blue crabs was not observed during a subsequent 28-day period, but pink shrimp lost mercury at a rate of about 0.012 day^{-1}. Model calculations predict biomagnification factors of mercury of about two to three at steady state for both species. The large difference in observed concentrations of mercury in field-collected blue crabs and penaeid shrimp does not result from differences in efficiency of mercury assimilation from their food or from differences in excretion rates. It is more likely the result of differences in residence times in the contaminated area and of differences in feeding habits. Published by Elsevier Science Ltd.

Keywords: Crabs; Shrimp; Mercury; Uptake; Depuration; Model-bioaccumulation; Trophic transfer; Assimilation efficiency; Biomagnification; Lavaca Bay; Texas

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1. Introduction

Mercury came to the forefront of environmental concerns in the 1960s and 1970s with cases of mercury poisoning such as occurred in Minamata Bay, Japan (Harada, 1966; Irukayama, 1967), and in Iraq (Bakir et al., 1973). Today there are approximately 34 states in the USA with fish consumption advisories for mercury [R. Hoffman (EPA), Washington, DC, personal communication]. However, only seven states have estuarine or marine areas closed to finfish and shellfish consumption due to levels of mercury greater than the Food and Drug Administration action level of 1.0 $\mu g\ g^{-1}$ wet weight as methyl mercury. One of these states is Texas, in which a chlor-alkali plant operated from 1966 to 1979 at Point Comfort, discharging mercury-contaminated wastewater from 1966 to 1970 into Lavaca Bay and into lagoons on a dredge material island in the bay west of the plant. As a result of monitoring by the Texas Department of Health for the past 29 years, a portion of Lavaca Bay (termed the "Closed Area", Fig. 1) has been closed to crab and fish harvesting for consumption since 1988.

Higher trophic level aquatic organisms accumulate mercury mostly from the food they consume (Wiener & Spry, 1996). In Lavaca Bay, most food organisms are thought to derive their mercury in turn from sediments which have retained high concentrations of mercury since plant closure (Evans & Engel, 1994). Total mercury concentrations in blue crabs and in some species of fish have remained elevated as

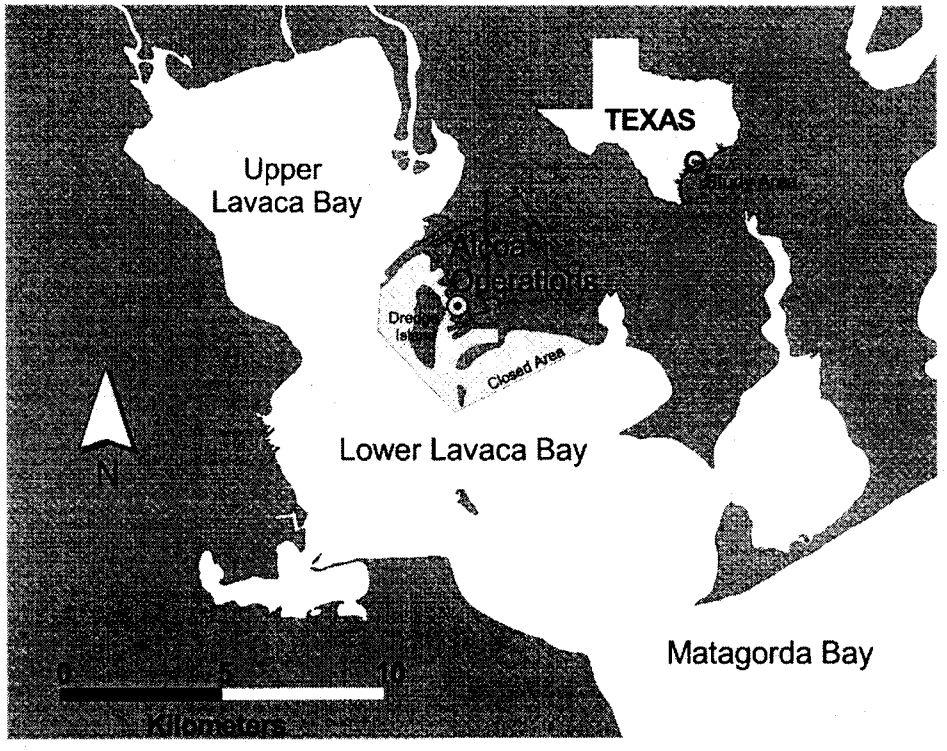

Fig. 1. Map of Lavaca Bay showing the area near Point Comfort closed to fishing and crabbing (Closed Area).

well, especially in and near the Closed Area. Since 1980, maximum measured concentrations of total mercury in muscle tissue have been 4.46 μg g^{-1} wet weight for blue crabs, 6.62 μg g^{-1} for black drum, 4.55 μg g^{-1} for red drum, 2.92 μg g^{-1} for sheepshead, and 1.68 μg g^{-1} for southern flounder (Texas Department of Health, 1993). In contrast, total mercury concentrations in muscle tissue of harvestable-sized penaeid shrimp have not been measured above 0.28 μg g^{-1} wet weight (Bowman, 1988). Historically, most mercury concentrations in such shrimp have been little different from the average of 0.07 μg g^{-1} wet weight for the state of Texas (Texas Department of Health, 1993). As a result, the area has remained open to commercial harvesting of shrimp.

Lower concentrations of mercury in shrimp compared to blue crabs may be due to either exposure to lower mercury concentrations or less efficient accumulation and retention of ingested mercury. Penaeid shrimp, like blue crabs, are opportunistic omnivores. They are less predatory than blue crabs, however, depending more on plants and detritus for food (Britton & Morton, 1989; McTigue & Zimmerman, 1991). Because mercury (or at least methyl mercury) is generally biomagnified along food chains (Suedel, Boraaczek, Peddicord, Clifford & Dillon, 1994), organisms feeding low on the food web would be expected to have lower mercury concentrations.

Exposure to lower mercury concentrations could also result if shrimp spend only limited time feeding in the most contaminated part of the bay (Closed Area). Palmer (1992) and Palmer and Presley (1993) transplanted both brown shrimp and blue crabs into the Closed Area of Lavaca Bay from distant areas with lower mercury exposures. With emigration from the Closed Area prevented by caging, it was possible to test if these organisms could acquire elevated concentrations of mercury. Juvenile brown shrimp more than tripled their total mercury concentrations in 36 days of exposure, from 0.05 μg g^{-1} wet weight (assuming a wet to dry wt. ratio of 7) to 0.17 μg g^{-1} wet weight. Resident adult shrimp in the Closed Area had lower total mercury concentrations (0.03 μg g^{-1} wet wt.: Woodward-Clyde Consultants, 1993; 0.03–0.13 μg g^{-1} wet wt.: Presley, Palmer & Boothe, 1993), suggesting that resident shrimp had spent less than 36 days in the Closed Area (Palmer & Presley, 1993). Surprisingly, transplanted juvenile blue crabs showed no significant statistical increase in total mercury concentrations. Although natural variability may have obscured real uptake of mercury by crabs (Palmer, 1992), the turnover time of mercury in blue crabs may be substantially longer than in shrimp. Given longer exposure times, substantial mercury uptake might have been observed in crabs.

We have examined the potential accumulation and retention of mercury by pink shrimp and blue crabs in laboratory experiments using food with known concentrations of naturally accumulated mercury. Our studies demonstrate the ability of these animals to accumulate mercury from their food. If both species have similar uptake patterns when presented with mercury-laden food, then the observation of lower mercury concentrations in field-collected shrimp from the Closed Area would indicate differences in mercury exposure; shrimp either feed on food of lower mercury concentration than do crabs, or they do not remain in the area of exposure long enough for significant accumulation to occur.

2. Materials and methods

2.1. Test organisms

Juvenile blue crabs (*Callinectes sapidus*) were collected from several sites within the Mississippi Sound estuary system near Ocean Springs, MS. Crabs were maintained in the laboratory in solutions of artificial sea salts (Forty Fathoms) at 25–28°C and 20–22‰ salinity under static renewal conditions for 9–11 days prior to exposure initiation. During the pre-exposure period, crabs were fed live or frozen adult brine shrimp (*Artemia* sp.) containing less than 0.03 μg g^{-1} mercury wet weight. Initial size of these juvenile blue crabs ranged from 22 to 36 mm carapace width (mean 27 mm) and 0.61 to 3.85 g wet weight (mean 1.63 g).

The pink shrimp (*Penaeus duorarum*) was selected as a test species for this study. It substituted for the brown shrimp (*Penaeus aztecus*) and white shrimp (*Penaeus setiferus*) more common in Lavaca Bay, to which it is taxonomically and ecologically related (Pérez Farfante, 1969). Pink shrimp nauplii were obtained from the US EPA Environmental Research Laboratory in Gulf Breeze, FL, and maintained under static renewal conditions. Over a 2-week period, culture water was gradually changed from natural seawater to artificial seawater (Hawaiian Marine Mix) to provide a controlled osmotic environment. Over a period of about 1 month, the salinity of the culture water was decreased from 28 to 20‰, to mimic average conditions in Lavaca Bay, where it was maintained through the remainder of the 12-week culture period. Culture temperature ranged from 27 to 29°C. During the culture period, shrimp were fed a diet of diatoms (*Chaetoceros gracilis*), *Artemia* nauplii, and a pelleted shrimp food (Zeigler Brothers Post Larval No. 4), either singly or in combination. These foods contained less than 0.03 μg g^{-1} mercury wet weight. These juvenile shrimp ranged in initial size from 41 to 56 mm in length (mean 48 mm) and from 0.56 to 1.41 g wet weight (mean 0.83 g).

2.2. Mercury-labeled food

Black drum (*Pogonias cromis*) were used as food for crabs and shrimp because fish were available at two levels of mercury concentration. Black drum collected by entangling nets in the Closed Area contained high concentrations of mercury (termed enriched black drum) and were used to feed the treatment crabs and shrimp during the uptake phase. Four fish were selected for use as food, each having total mercury concentrations greater than 1.0 μg g^{-1} wet weight. Additional black drum of low mercury concentration were readily available from commercial suppliers (Quality Seafood) in Austin, TX, and were termed baseline black drum. Their mercury concentration averaged 0.13 μg g^{-1} wet weight. They served as food for treatment crabs and shrimp during the depuration phase and for control crabs and shrimp. Fish were taken to an on-site laboratory, where they were scaled, the muscle tissue removed from both sides of each fish, and the skin removed from each of these filets. Filets from individual fish were cut into approximate 3.5-cm^3 cubes. A sample from each fish was sent to an analytical laboratory for total mercury analysis. The

cubes from each fish were kept separate and mixed and frozen in packages of approximately 140 cubes (500 g) per package. Both the enriched and the baseline black drum were sampled periodically throughout the study to monitor the stability of mercury content under storage conditions. Individual portions of black drum to be fed to the test animals during the study were weighed onto aluminum foil pieces, wrapped, and refrozen. Samples of food were randomly removed from the weekly portion and accompanied the control and treatment animals sent to the analytical laboratory for mercury analysis.

Recent studies have found that methyl mercury is a large fraction of the total mercury in the flesh of black drum from Lavaca Bay (86%: Woodward-Clyde Consultants, 1993; 77%: Texas Department of Health, 1993). Assimilation efficiencies for methyl mercury are generally much higher than for inorganic mercury in fish (Pentreath, 1976), shrimp (Fowler, Heyraud & La Rosa, 1978; Riisgård & Famme, 1986) and crabs (Bjerregaard & Christensen, 1993). Although we did not specifically analyze for methyl mercury, the accumulation and excretion of mercury determined in this study is most likely that of methyl mercury.

2.3. Mercury analysis

All biological tissue samples were analyzed for total mercury by cold vapor atomic absorption spectroscopy following modified EPA method CLP SOW ILM02.0. The method closely follows EPA's Method 245.6, "Determination of Mercury in Tissues by Cold Vapor Atomic Absorption Spectrometry" (EPA, 1991), with substitution of sodium borohydride for stannous chloride as the reductant. Composite samples of whole crabs or shrimp were homogenized and 2-g sub-samples digested in a mixture of sulfuric and nitric acids with additions of potassium persulfate and potassium permanganate. Mercury was determined with a Leeman Labs PS200 automated mercury analyzer. Mercury was determined at a wavelength of 253.7 nm by comparing the absorbance of the unknown samples with the absorbances of the standard solutions. Concentrations are reported on a wet weight basis.

Matrix spikes, matrix duplicates and blanks were included during the procedures to ensure acceptable accuracy and precision. Analysis of the certified reference material, DORM-1, yielded a mean measured concentration of 0.95 $\mu g\ g^{-1}$ with a standard deviation (SD) of 0.05 $\mu g\ g^{-1}$ ($n=22$). The certified concentration is $0.80 \pm 0.07\ \mu g\ g^{-1}$. Spike recoveries averaged $96 \pm 13\%$. Duplicate analyses differed by an average of 6%. The detection limit for tissue was 0.03 $\mu g\ g^{-1}$ wet weight (based on three SDs of the blanks).

2.4. Study design

For each test species, the study included a control and a treatment group, each replicated three times. At the time of first feeding, there were 32 animals per control replicate and 64 animals per treatment replicate. During the uptake phase (days 0–28), control animals were fed baseline black drum of low mercury concentration, while treatment animals were fed enriched black drum of an order of magnitude

greater mercury concentration. On day 28, all remaining control animals were sacrificed; all remaining treatment animals continued into the depuration phase, during which time (days 28–56), they were fed baseline black drum with low mercury concentration.

Test aquaria were constructed of glass and measured 155 cm long by 30 cm wide by 20 cm high for the control groups, and 155 cm long by 53 cm wide by 20 cm high for the larger exposed groups. Water used during testing was prepared from artificial sea salts (Forty Fathoms), adjusted to a salinity of between 20 and 21‰ with unchlorinated well water and aged for at least 2 days. Water was recirculated through a 10-μm particle filter and a carbon filter, and intensively aerated to ensure a dissolved oxygen level of at least 90% saturation prior to use. Water depth was 8 cm in all test aquaria. To ensure that accumulated debris and fecal matter did not compromise water quality, a complete water exchange was provided daily to each test aquarium.

For each test species, aquaria containing the test animals were positioned in a heated recirculating water bath to maintain temperature at 25 ± 1°C. Each water bath was completely enclosed with a curtain to shield the test animals from outside disturbances. A 12 h light/12 h dark photoperiod with a 30-min dimmer to simulate dusk and dawn was provided.

Within the aquaria, shrimp and crabs were individually isolated into numbered holding chambers to preclude cannibalism and to ensure that all test organisms were provided with equal amounts of food during the study. The holding chambers were 100-mm diameter by 15-mm glass Petri dish bottoms with an attached 15-cm high cylindrical collar of 750-μm nylon mesh. Holding chamber numbers were used to identify the individuals to be removed at each sampling and to reference observations recorded on individual animals.

Crabs were held in test aquaria for 9 days and shrimp for 4 days prior to first feeding with black drum to acclimate them to test conditions. Eight crabs were composited from each aquarium prior to first feeding with black drum to determine initial levels of mercury. Similar composites of eight shrimp from each aquarium were also analyzed for mercury.

Crabs and shrimp were fed black drum once daily throughout the study. Initially, each food portion weighed 0.10 g, or 10% of the anticipated average initial body weight of 1 g for each test species. Subsequently, feeding portions were adjusted to maintain the feeding level at 8–10% of the average weight of animals sampled each week. However, to preclude the compromising of water quality during the depuration phase, food amounts prescribed on the basis of animal weights were not increased if uneaten food was present in most holding chambers 24 h after feeding.

Animals were observed daily for mortality, molting, and any changes in physical appearance or behavior. Dissolved oxygen, pH, salinity, and temperature were measured twice weekly, generally prior to the daily water change.

Animals were sampled for mercury analysis on day 0 and at subsequent 7-day intervals during the course of the study. Individual animals were selected for compositing by predetermined random number sequences. Eight animals from each replicate tank comprised a composite sample for analysis. Some composites from

later sampling times consisted of fewer than eight animals, however, since adjustments for mortality were not made. Chambers containing the animals to be sampled were removed from the test aquaria, and placed into beakers of chilled dilution water. Animals were removed when inactive, blotted dry, measured to the nearest millimeter, and weighed to the nearest milligram.

3. Results

Neither crabs nor shrimp grew much during the first 2 weeks in either treatment or control groups. Over an 8-week period, treatment crabs grew at an average rate of 1.8% wet weight day^{-1}; shrimp grew more slowly at a rate of 0.6% wet weight day^{-1} (Fig. 2). Comparable rates are found for the 28 days of the control groups. These rates of growth are substantially less than those expected for free-living blue crabs and penaeid shrimp.

The molt frequencies were similar for control and treatment crabs during the shared days 0–28 uptake period. This was also the case for shrimp. The molt frequency was higher on average for shrimp (0.27 week^{-1}) than for crabs (0.22 week^{-1}). Over the 8-week study, shrimp experienced cumulative 28% mortality and crabs only 6% mortality. Most deaths occurred during the depuration period. Mortality rates were similar for control and treatment groups during the accumulation period for

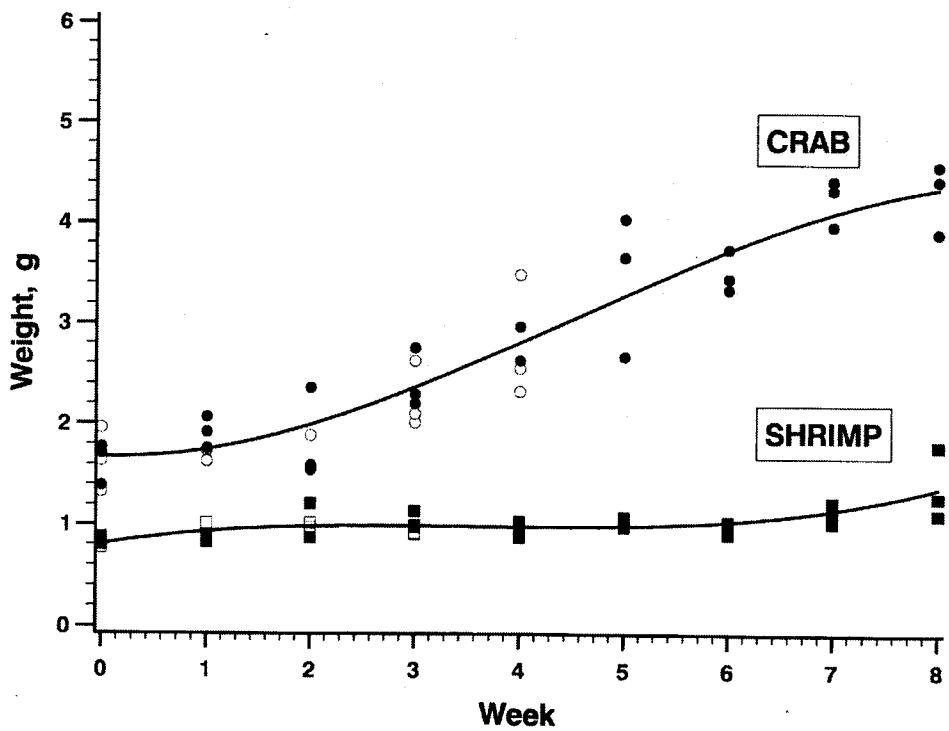

Fig. 2. Observed growth in blue crabs and pink shrimp over an 8-week period of study. Closed symbols are treatment animals. Open symbols are control animals.

both crabs and shrimp, suggesting that mercury exposure was not the cause of mortalities.

Throughout the experiments, temperatures ranged from 24 to 26°C, pH from 8.2 to 8.7, salinity from 20 to 21‰, and DO from 3.0 to 8.5 mg l^{-1}.

During 28 days' feeding on mercury-enriched food, both crabs and shrimp attained whole-body mercury concentrations nearly equal to concentrations in their food source (Fig. 3). In the control groups crabs and shrimp increased their mercury concentrations from 0.03 μg g^{-1} to levels nearly equal to the much lower average mercury concentration (0.13 μg g^{-1}) in their baseline food source (not shown).

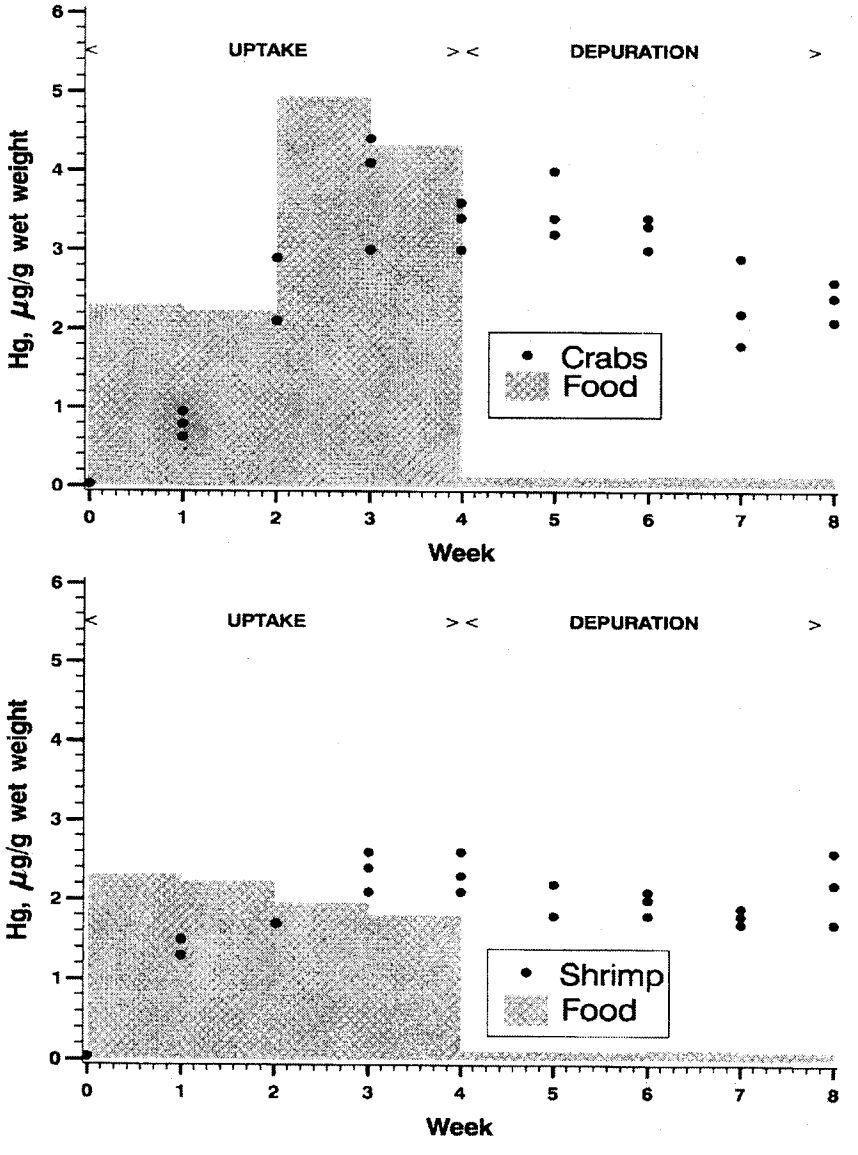

Fig. 3. Mercury (Hg) concentrations in treatment blue crabs and pink shrimp (closed symbols, broad line) and their food (bars) during uptake period (days 0–28) and depuration period (days 28–56).

During the depuration phase (days 28–56), average mercury concentrations declined moderately for both crabs and shrimp (Fig. 3). However, this decline in mercury concentrations does not mean that mercury was actually excreted. Growth in biomass can lead to declines in mercury concentrations through "growth dilution" (Niimi, 1983), which can occur even in the absence of any mercury excretion.

It is possible to fit these data to a simple mass-balance model of mercury accumulation and loss which incorporates growth dilution. This is done explicitly by modeling the mass of mercury (weight×concentration) rather than the concentration of mercury in the organism:

$$\mathrm{d}M/\mathrm{d}t = \alpha I - kM, \tag{1}$$

where $\mathrm{d}M/\mathrm{d}t$ is the rate of change of the mass of mercury in the organism, I is the intake rate of mercury in food, α is the assimilation efficiency of mercury from food, M is the mass of mercury in the organism, and k is the first order excretion rate constant of mercury from the organism.

$$I = C_f R, \tag{2}$$

where R is the food ration and C_f is the mercury concentration in the food. Ration was determined by adjusting the presented food to correct for uneaten food. Both ration and the mercury concentration varied over time. After 2 weeks of uptake, treatment crabs were supplied food from a second enriched black drum of double the mercury concentration of the first 2-week period (Fig. 3).

We fit the observed data to the integral form of Eq. (1), because mercury inputs from food were not constant. The integrated equation (Hess, Smith & Price, 1975) is:

$$M_t = \mathrm{e}^{-kt}(M_0 + \alpha \int I_t \mathrm{e}^{+kt} \mathrm{d}t), \tag{3}$$

where M_t is the mass of mercury at any given time t, M_0 is the initial mercury content in the feeding organism ($M_0 = C_0 W_0$, where W_0 is the initial organism weight and C_0 is the intial mercury concentration), I_t is the sum of ingested mercury during the prior time period, and $\mathrm{d}t$ is the time interval between samples (i.e. 7 days). Eq. (3) was solved for the unknown parameters, α and k, using non-linear methods in SAS procedure NLIN (SAS Institute, Cary, NC). We weighted the analyses by the number of animals making up the composite at each sampling period. A brief elaboration of our approach to concurrent parameter estimation is found in the Appendix.

Calculated mercury assimilation efficiencies were high for treatment crabs (76 ± 7% SE). Mercury assimilation efficiencies for treatment shrimp were also high (72 ± 7% SE). These high assimilation efficiencies are similar to reported assimilation efficiencies of methyl mercury in crabs (Bjerregaard & Christensen, 1993; Larsen & Bjerregaard, 1996) and shrimp (Fowler et al., 1978; Riisgård & Famme, 1986).

Calculated excretion rate constants of mercury were not significantly different from zero for treatment blue crabs ($k = -0.002 \pm 0.004$ day^{-1} SE). Growth dilution in crabs gives the false impression of mercury loss during the depuration period (Fig. 3). Excretion rate constants of mercury in treatment pink shrimp were significant at $k = 0.012 \pm 0.005$ day^{-1} SE). Growth dilution was not important for shrimp. Previously reported excretion rate constants for methyl mercury in both shrimp and crabs are small, on the order of 0.001–0.003 day^{-1} (Fowler et al., 1978; Larsen & Bjerregaard, 1996; Miettinen, Heyraud & Keckes, 1972; Renzoni, Bacci & Falciai, 1973).

These parameters can be applied to the ingestion data for control crabs and shrimp to predict mercury accumulation during exposure to much lower mercury concentrations for 4 weeks duration. Predicted concentrations are very close to observed concentrations for control crabs, but slightly high for control shrimp (Fig. 4).

It is possible to use the measured mercury assimilation coefficients and excretion rates in combination with estimated growth and growth efficiencies of blue crabs and penaeid shrimp to estimate the steady-state concentrations of mercury in their food (C_f) that would support observed concentrations in organisms from the Closed Area of Lavaca Bay. Eq. (1) can be rewritten:

$$d(CW)/dt = W dC/dt + C dW/dt = \alpha C_f R - kCW. \quad (4)$$

At steady state, $dC/dt = 0$, the growth rate is $G = dW/dt$, and $R = G/\epsilon$, where ϵ is the gross growth efficiency. If $g = G/W$ is the weight specific growth rate then:

$$C_f = C/f, \quad (5)$$

where $f = (\alpha/\epsilon)g/(g+k)$ is the food chain transfer number or biomagnification factor in the sense of Thomann (1981). Calculated biomagnification factors for crabs and shrimp are similar at 3.0 and 2.5, respectively. Predicted mercury concentrations in prey items supporting the observed concentrations in these two species differ by about four-fold (Table 1).

4. Discussion

Clearly, lower concentrations of mercury in Lavaca Bay shrimp cannot be due to a lower efficiency of mercury assimilation if food comparable to fish flesh is being consumed. The efficiencies of assimilation of mercury are high enough and the kinetics of excretion are slow enough in both blue crabs and pink shrimp that they can biomagnify methyl mercury to about two to three times the concentration in their food, at steady state. This biomagnification factor is largely determined by the value of the gross growth efficiency, ϵ, a conclusion reached long ago by Isaacs (1972). Because gross growth efficiency decreases with age, in fish at least (Pauly, 1986), older organisms can accumulate methyl mercury to higher levels than more

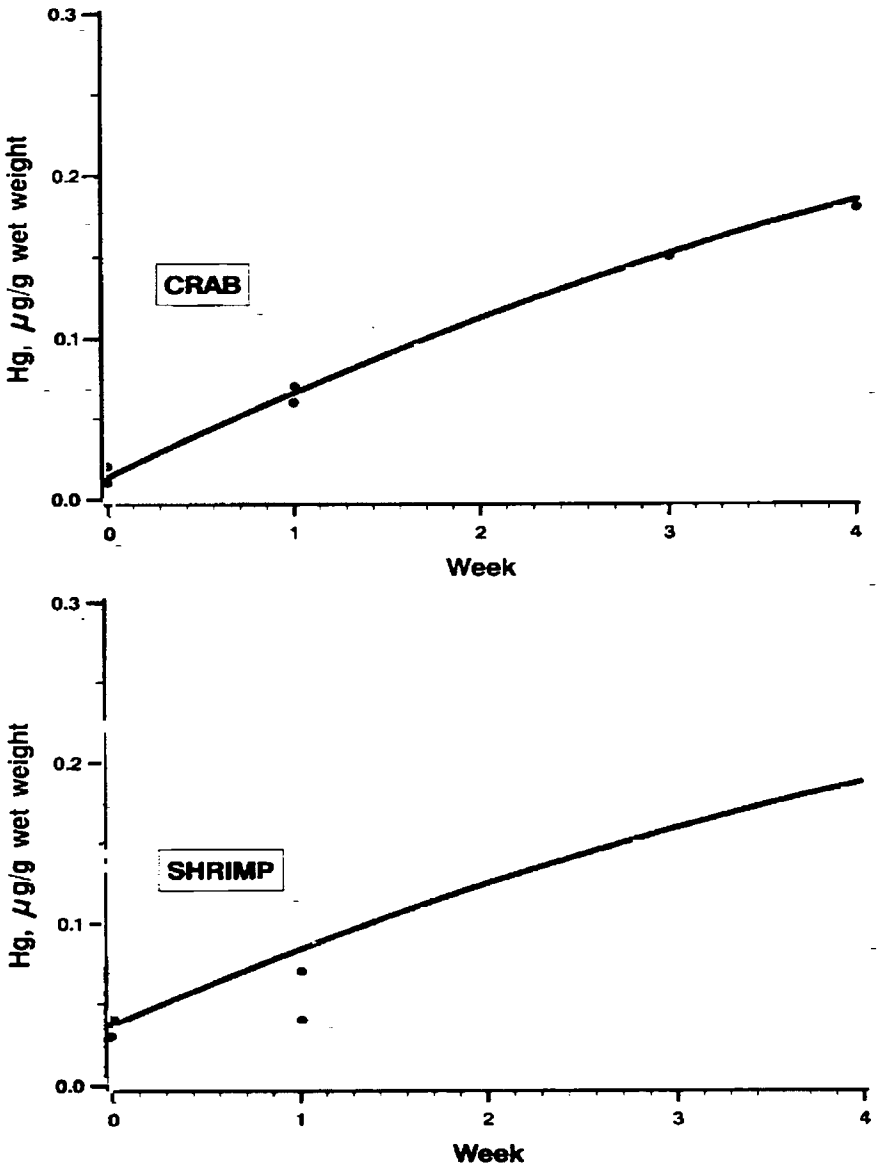

Fig. 4. Observed bioaccumulation of mercury (Hg) in blue crabs and pink shrimp feeding on control black drum flesh averaging 0.13 μg/g wet weight Hg (closed symbols). Predicted concentrations are shown as a solid line and were calculated with parameters from the treatment exposures.

rapidly growing younger ones. In freshwater environments the average mercury or methyl mercury concentration ratio between trophic levels is typically 2–5 (Cabana, Tremblay, Kalff & Rasmussen, 1994; Kidd, Hesslein, Fudge & Hallard, 1995; Watras & Bloom, 1992). Similar biomagnification factors are found in estuarine and marine environments (Young et al., 1980).

Accumulation of methyl mercury by aquatic organisms depends on both the duration and magnitude of exposure. It is not possible to directly distinguish whether adult penaeid shrimp in the Closed Area of Lavaca Bay acquire seemingly low concentrations of mercury because of limited duration in the area or feeding on

Table 1
Parameters used in calculating mercury concentrations of food required to support steady-state bioaccumulation in crabs and shrimp

Parameter	Crab		Shrimp	
	Value	Reference	Value	Reference
C_0	0.76 μg g^{-1}	Texas Department of Health, 1993	0.17 μg g^{-1}	Palmer and Presley, 1993
g	0.03 day^{-1}	Tagatz, 1968	0.03 day^{-1}	Rothschild and Brunenmester, 1984
k	0.000 day^{-}	This study	0.012 day^{-1}	This study
	0.76	This study	0.72	This study
ϵ	0.25	Holland, 1971	0.22	Ibrahim, 1973
f	3.0	Eq. (4)	2.5	Eq. (4)
C_f	0.25 μg g^{-1}	Eq.(5)	0.07 μg g^{-1}	Eq. (5)

food of particularly low mercury concentration. Stable nitrogen isotope analysis, however, confirms their relatively low trophic level compared to blue crabs (Montagna & Kathman, unpublished data). Recent measurements (Woodward-Clyde Consultants, 1993) found that adult white shrimp in the Closed Area contain an average of 0.03 μg g^{-1} total mercury. There are few potential foods for shrimp in the area that do not have higher mercury concentrations than the shrimp themselves (Locarnini & Presley, 1996; Presley et al., 1993; Woodward-Clyde Consultants, 1993). It would thus appear that limited duration of feeding in the Closed Area is the major explanation for low mercury concentrations in adult shrimp. Supporting this conclusion is the observation that adult shrimp sampled outside the Closed Area contained the same average mercury concentration, 0.03 μg g^{-1}, as those inside the Closed Area (Woodward-Clyde Consultants, 1993). Within the Closed Area, small juvenile shrimp have higher mercury concentrations than adult-sized shrimp (Presley et al., 1993). This is consistent with the life history of shrimp in which juveniles use estuarine marshes as nursery grounds before migrating to coastal waters as sub-adults for spawning. As such, juveniles could be exposed to localized estuarine mercury concentrations that migrating adults would avoid.

We can extend this reasoning and conclude that those species with similar mercury concentrations inside and outside the Closed Area also spend little time feeding in the Closed Area or else they feed on a food web not supported directly by the mercury in contaminated sediments. Species whose mercury concentrations differ little inside and outside the Closed Area (within a factor of 2) are those such as menhaden which are pelagic filter feeders, spotted seatrout which feed predominantly on mobile fish and shrimp, and other fish which feed pelagically or move extensively in the estuary (Woodward-Clyde Consultants, 1993).

Species with elevated mercury concentrations in the Closed Area (more than a factor of three times those outside the Closed Area) are sessile organisms or mobile organisms with restricted movements. Sessile organisms include clams, oysters,

hooked mussels, cordgrass, benthic algae, and sediment inhabiting polychaete worms. Mobile species with restricted movements typically use marsh or other structured environments as feeding habitat or refuges from predation. These latter include grass shrimp and marsh forage fish which are associated with cordgrass, sheepshead which are associated with vertical structure, and the benthic feeding red drum, black drum and blue crabs which are the predators whose high mercury concentrations warrant the greatest concern (Texas Department of Health, 1993; Woodward-Clyde Consultants, 1993).

Home foraging range, seasonal and annual movements, and feeding habits are critical issues in determining exposure to mercury contamination in Lavaca Bay that need further study.

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Appendix

Estimation of assimilation efficiencies (α) and excretion rate constants (k) is an effort to solve a mass-balance problem with coupled inputs and losses. Eq. (1) is the formulation of a simple mass-balance equation for a single compartment with input from feeding (ingestion) and loss (excretion) proportional to the retained mass of substance in the compartment (i.e. first order with constant coefficient). Historically, researchers have sought to structure experiments to determine α or k separately, under conditions that minimize the effect of one process on the the other. Thus, α is often estimated during a short feeding period before significant excretion has occurred. Typically, researchers calculate α as a point estimate of the ratio of retention to cumulative ingestion at some time during the uptake period. Likewise, k is usually estimated during the depuration period when no further inputs are operating. In some cases, α can be estimated during a depuration period under an assumption of multi-compartment loss by back stripping the loss curve to estimate transient accumulation in a gastrointestinal (GI) tract compartment, but this method makes assumptions about the clearance time of the GI tract (Reinfelder, Fisher, Luoma, Nichols & Wang, 1998).

Fig. A1 shows a plot of the time trend in mercury accumulation over a 20-day period for a hypothetical one-compartment system in which the excretion rate

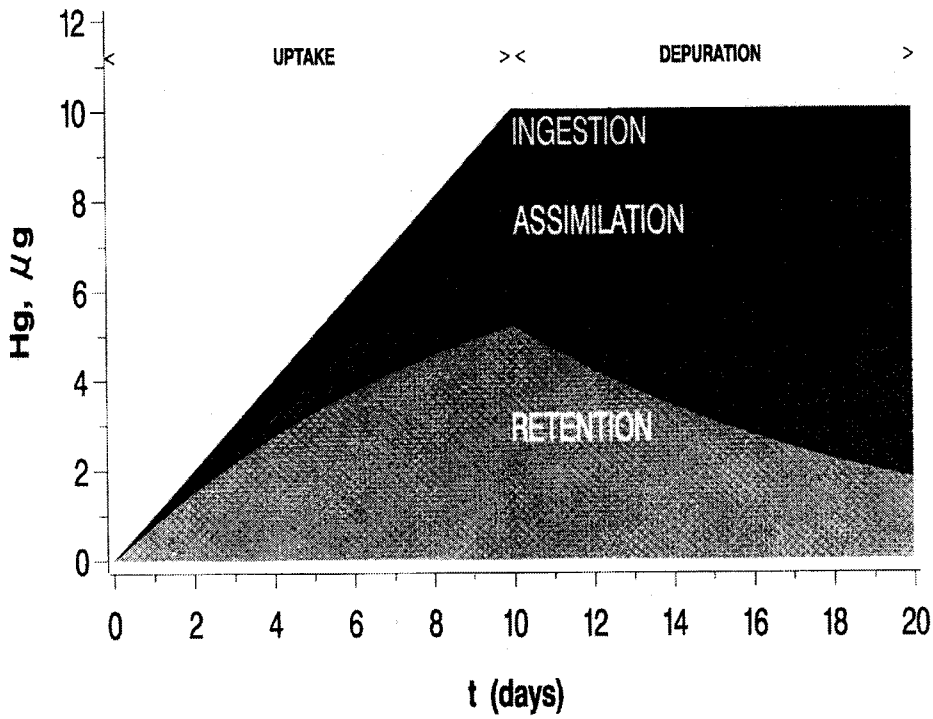

Fig. A1. Hypothetical accumulation of mercury (Hg) according to Eq. (1) assuming ingestion of 1 μg Hg day^{-1} for the 10-day uptake period and 0 for the subsequent 10-day depuration period; $\alpha = 0.8$ and $k = 0.1$ day^{-1}.

constant, $k = 0.1$ day^{-1}, assimilation efficiency, $\alpha = 0.80$, and mercury is ingested at a rate of 1 μg day^{-1} for the first 10-day uptake period and 0 μg day^{-1} for the 10-day depuration period. Throughout both periods, retention is less than assimilation because of excretion, and the ratio of retention to ingestion underestimates assimilation efficiency. Estimates of α are least biased early in the uptake period, before excretion losses have accumulated to any extent ($\alpha I \gg kM$). Similarly, k is best estimated early in the depuration period when retention is near its maximum and ingestion is small ($kM \gg \alpha I$).

In our approach to estimating α and k, we employed all of the data during both uptake and depuration to solve simultaneously for α and k because assimilation and excretion operate simultaneously. This allowed our estimates of α and k to jointly constrain one another and gain greater statistical degrees of freedom in estimation by using all of the data points. In addition, ingestion of mercury was not constant during the uptake period which obviated a simple analytical solution. There was also a low level of continued mercury ingestion (non-zero mercury in the food) during the depuration period that was not trivial in relation to the low excretion rates observed.

Operationally, Eq. (4) is specified for every point in time when M is measured, at:

$$t = 0 \quad M = M_0$$

$$t = 1 \quad M = M_0 e^{-k} + \alpha I_1$$

$$M = M_0 e^{-2k} + \alpha I_1 e^{-k} + \alpha I_2$$

$$M = M_0 e^{-3k} + \alpha I_1 e^{-2k} + \alpha I_2 e^{-k} + \alpha I_3, \quad \text{etc.}$$

The values of I_1, I_2, I_3, etc., are the ingested amounts of mercury during the interval since the last measurement of M. Given the measured values of I_t, it is straightforward to solve for the two unknowns α and k by non-linear regression procedures, as we have done.

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