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PILOT TRANSPLANT STUDIES WITH THE INTRODUCED
ASIATIC CLAM, CORBICULA FLUMINEA, TO MEASURE
METHYL MERCURY ACCUMULATION IN THE FOODWEB OF
THE SACRAMENTO-SAN JOAQUIN DELTA ESTUARY

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Abstract

A series of control and transplant studies were conducted with the introduced Asiatic clam, *Corbicula fluminea*, to determine both the temporal and spatial pattern of methyl mercury uptake in the pelagic food web of the Sacramento-San Joaquin Delta and the primary factor(s) controlling it.

Three control experiments were undertaken. First, composite fish and clam samples were collected from the Delta and from its freshwater tributaries in 1999 and 2000. A positive correlation was observed between methyl mercury tissue concentrations in clams and in four of the nine fish species examined (Largemouth bass, Redear sunfish, Sacramento suckers, and Inland silversides). The results suggested that the clam might serve as a model for studying methyl mercury uptake in a portion of the Delta food web.

Second, control studies were undertaken to determine whether caged clams could be used as surrogates for methyl mercury uptake and depuration in the wild population. Methyl mercury tissue concentrations of caged and wild clams in Putah Creek and in the Sacramento River at Rio Vista were measured monthly and found to be similar for the ten months of joint exposure (P>0.25). The conclusion is particularly robust at Putah Creek as wild and caged clams lost half their methyl mercury (240 to 142 ppb dry weight) and regained it during the study.

A third control experiment was undertaken to determine the potential rate of methyl mercury uptake and depuration. Clams were transplanted from the Sacramento River to Putah Creek (low to high methyl mercury environment) and vice versa. Clams in the reciprocal transplant took two and four months, respectively, to become similar to the surrounding wild population. In conclusion, the caging experiments suggested that transplanted animals could be used as a surrogate for studying methyl mercury dynamics in the wild population if held for at least four months.

Four thousand clams were collected in February 2001 and transplanted into replicate cages at six locations in the Estuary and in the freshwater tributaries. Changes in clam methyl mercury body burden, tissue weight, and a suite of water quality parameters were followed monthly at each site. Change in clam methyl mercury tissue concentration can be expressed as:

\[ \Delta \text{Tissue Concentration} = \frac{\Delta \text{Body Burden}}{\Delta \text{Dry Tissue Weight}} \]

Where the units in equation 1 for \( \Delta \) tissue concentration are ng-methyl mercury-gm tissue weight\(^{-1}\), \( \Delta \) body burden is ng-methyl mercury-clam\(^{-1}\), and \( \Delta \) dry tissue weight is gm-clam\(^{-1}\).

Most of the methyl mercury uptake, as well as change in tissue growth, occurred between March-June in the Delta. The rate of methyl mercury uptake was more variable than tissue growth. The initial body burden of pre-transplanted clams was 60-ng methyl mercury and increased during the seven-month exposure to 95-330 ng, a 0.6 to 4.5-fold increase. In contrast, tissue weight increased from 0.6 to 1.4 to 1.7-gm or a 1.3 to 1.8-fold change. The results demonstrate that site-specific tissue concentrations are primarily determined by the uptake and depuration of methyl mercury.

The rate of change in clam methyl mercury body burden per month was positively correlated to unfiltered methyl mercury divided by the sum of the chlorophyll and phaeophytin concentration in ambient water \( (R^2 = 0.42, P = 6 \times 10^{-5}) \). Change in tissue growth was positively related to the sum of the chlorophyll and phaeophytin concentration \( (R^2 = 0.46, P<0.01) \). Substituting the two field relationships into equation 1 and simplifying results in:

\[ \Delta \text{Tissue Concentration} = \frac{\text{Methyl Mercury Concentration}}{(\text{Chlorophyll} + \text{Phaeophytin})^2} \]

Results from the clam transplant study were used to develop a conceptual model of methyl mercury accumulation in primary consumers in the Sacramento-San Joaquin Delta.
Introduction

Methyl mercury is a potent human and wildlife neurotoxin with fetuses and the very young being most at risk (White et al., 1995; Wolf et al., 1998). The principal route of exposure is through consumption of mercury contaminated fish. In 1971 a human health advisory was issued for the Sacramento-San Joaquin Bay-Delta Estuary (Bay-Delta Estuary) advising pregnant women and children not to consume striped bass. The advisory was re-released in 1994 upon review of more data (OEHHA, 1994). Recently, the National Academy of Sciences (2000) recommended a methyl-mercury intake rate of less than 100-ng kg⁻¹ body weight per day to protect human health. This is equivalent to the consumption of less than two meals a month of fish containing 0.3-ppm mercury wet weight (U.S. EPA 1999). Similarly, the U.S Fish & Wildlife Service is recommending a methyl mercury concentration of less than 0.2-ppm in forage fish to protect threatened and endangered piscivorous birds (U.S. Fish & Wildlife letter of April 2002). Tissue concentrations of several common game and forage fish in the Central Valley and Bay-Delta Estuary exceed these values (Davis et al., 2002; Slotton et al., 2002) suggesting that mercury contamination may be a greater human and wildlife health risk than previously recognized.

Ninety percent of the mercury (100 million kg) used in the United States between 1850 and 1988 was mined in the coast range of California (Churchill, 1999). Much of the mining and extraction occurred prior to 1890 when mercury processing was crude and inefficient. About thirty million kg of mercury are estimated to have been lost in and around the Coast Range mercury mines (Churchill, 1999). Eight million kg of this mercury was transported across the valley and used in placer and lode gold mining in the Sierra Nevada’s between 1850 and 1890 (Churchill, 1999). All this mercury was probably lost in the gold fields. As a result, widespread sediment contamination occurred in Coast Range and in Sierra Nevada rivers and downstream in the Central Valley and Bay-Delta Estuary.

Methyl mercury tissue concentrations in piscivorous fish in California are about million times higher than aqueous concentrations (see Foe (2002) for water and Davis et al (2002) and Slotton et al (2002) for fish tissue concentrations). Field studies demonstrate that methyl mercury biomagnification in the aquatic food web is a dietary phenomenon with concentrations progressively increasing at higher trophic levels. The largest increase occurs between water and phytoplankton (Plourde et al., 1997; Paterson et al., 1998; Watras et al., 1998; Watras and Bloom 1992; Bowles et al., 2001). Phytoplankton are capable of concentrating methyl mercury 10³ to 10⁶-fold above water values while succeeding trophic levels magnify concentration only 3-5 fold more (Watras and Bloom, 1992; Back and Watras, 1995; Mason and Sullivan, 1997; Monson and Brezonik, 1998). A potential confounding factor in these observations is that field assessments of mercury contamination in phytoplankton are derived from measurements of seston¹. Seston is a combination of inorganic and organic matter, including phytoplankton. Because of phytoplankton’s microscopic size, precise measurements of its mercury concentration is

¹ Everything accumulating on a 0.45 micron filter.
not possible. However, laboratory experiments with pure algal cultures support the conclusion that much of the biomagnification happens in living phytoplankton cells (Mason et al., 1995; Mason et al., 1996; Lawson and Mason, 1998; Pickhardt et al., 2002). The magnitude of methyl mercury accumulation in primary producers emphasizes the need for a good understanding of the temporal and spatial nature of uptake and transfer through this critical trophic level.

_Corbicula fluminea_, the introduced Asiatic clam, is the most common benthic invertebrate (biomass) in the Bay-Delta Estuary. The filter feeding clam’s diet is not completely understood but phytoplankton is an essential element (Foe and Knight, 1985). A positive correlation was observed in 1999 between methyl mercury tissue concentration in the clam and in a variety of game and forage fish in the Bay-Delta Estuary. The result suggests that it might be possible to ascertain the seasonal flux of methyl mercury from phytoplankton to higher trophic levels by following changes in clam tissue concentration.

_Corbicula_ has previously been placed in cages and tissue growth and metal accumulation measured (Foe and Knight, 1986). The seasonal pattern of growth and metal uptake was followed in caged animals and in the surrounding wild population at a control site. Both tissue growth and metal uptake was similar suggesting that caged individuals could be used as surrogates for the wild population. The authors are now collecting aqueous mercury concentrations in the estuary as part of a CALFED mercury mass load study (Foe, 2002). This suggested a unique opportunity to combine measurements of unfiltered aqueous methyl mercury with measurements of change in tissue concentration of transplanted clams. The primary objective being to attempt to determine the temporal and spatial pattern of methyl mercury uptake in the food web of the Bay-Delta Estuary by measuring changes in mercury concentrations in clams. A second objective was to attempt, if possible, to determine the primary factor(s) responsible for methyl mercury accumulation in _Corbicula_.

Method and Materials

Control Experiments

Three control experiments were undertaken to help interpret the clam transplant studies. First, a positive correlation was observed in 1999 between methyl mercury tissue concentrations in clams and a number of common fish species in the Bay Delta Estuary including largemouth bass (*Micropterus salmoides*). However, in each case the observations were based upon a small sample size. Therefore, additional sampling was undertaken in the summer of 2000 to ascertain whether a similar positive tissue correlation would be observed again. The sampling emphasized largemouth bass and clams but other fish were also analyzed if collected in sufficient numbers. Composites of five largemouth bass and 20-30 clams were made at 14 locations in the Estuary and its tributaries. Both years of data were combined for a multi year assessment of the correlation of methyl mercury in clam and fish tissue.

A second control experiment consisted of collecting several hundred clams in August, 2000, from both the Sacramento River at Rio Vista and from Putah Creek at Davis (Figure 1), sorting them into 5 mm shell length size classes, depurating and analyzing them to determine their methyl mercury tissue concentration. Purpose of the experiment was to ascertain whether tissue concentration changed as a function of clam size as clams of a mixed length were used in the correlation with fish. Depuration consisted of holding clams in aerated laboratory water at ambient temperatures for 3 days to void their guts of foreign material. Laboratory water was changed daily during depuration.

A third control experiment consisted of collecting about 500 clams of a narrow size range from both the Sacramento River at Rio Vista and from Putah Creek and randomly dividing each into two groups. Half of the animals from each location were transplanted into three replicate cages at the site where they were collected. The other half was transported to the opposite location and placed in similar sets of replicate cages. Wild clams of the same size were also collected from each location for analysis. The purpose of transplanting animals into cages at the location where they were collected was to determine whether caged clams would exhibit similar seasonal changes in methyl mercury concentration as wild animals from the same location.

The second control experiment, effect of clam size on mercury tissue concentrations, demonstrated that clams from Putah Creek had about 2.5 times more methyl mercury than did animals from the Sacramento River. The purpose of transplanting clams from Putah Creek to the Sacramento River (high to low methyl mercury environment) was to take advantage of this difference in body burden and determine potential rates of clam methyl mercury depuration. Similarly, the goal of transplanting clams from the Sacramento River to Putah Creek (low to high methyl mercury environment) was to ascertain potential rates of methyl mercury uptake. Eight clams were harvested monthly between October 2000 and July 2001 from each cage, composited into a single sample.

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2 305-438 mm body length
3 18-22 mm shell length at Putah Creek and 18-21 mm at Rio Vista.
per cage, depurated, and analyzed for methyl mercury concentration (3 replicate samples treatment\(^1\) month\(^{-1}\)). Also, on each occasion thirty wild clams, of as similar a size as the caged animals as possible, were collected, divided into three replicates and also analyzed for methyl mercury.

**Second Clam Transplant Experiment**

Four thousand clams\(^4\) were collected from the Sacramento-San Joaquin Bay-Delta at Big Break in late February 2001 and transplanted into replicate cages at eleven locations around the Estuary. Eight to ten clams were harvested monthly between April and October from three cages at each location for measurement of methyl mercury tissue concentrations (three composite samples-site\(^{-1}\) month\(^{-1}\)). Purpose of the transplant was threefold. First, to ascertain whether the caging technique could be successfully employed in a variety of aquatic habitats including small and large rivers and the estuary. Second, ascertain how methyl mercury tissue concentration changed seasonally in the different environments and, finally, if possible, determine water quality constituents responsible for controlling clam tissue levels.

**Cage units**

Cages were constructed as described in Foe and Knight (1986). Briefly, cage halves were made from plastic fluorescent-light egg-crate-type paneling and covered with polyethylene screen of an 11-mm square mesh\(^5\) (Figure 2). The screen was secured to the paneling with plastic cable ties. Cage halves were bound together with plastic bolts. Individual cage compartments measured 30 x 30 x 18-mm and contained a single clam. In the field, cages were secured about half a meter off the bottom in an upright position with heavy duty plastic cable ties to metal rebar driven into the substrate. The rebar was painted with a coat of flexible Plasti Dip rubber to minimize oxidation. All cages were located in sub tidal areas; care being taken to minimize clam exposure to air while removing animals for tissue analysis. Finally, cages were located, if possible, one to several hundred yards apart at each station to maximize the potential for assessing field variability.

**Water Quality Parameters**

A suite of water quality parameters that might explain changes in methyl mercury tissue concentration was measured monthly at each site during the second transplant. These included raw and filtered aqueous total and methyl mercury, temperature, total suspended solids (TSS), volatile suspended solids (VSS), chlorophyll \(\alpha\) and phaeophytin. Collection of water for measurement of mercury employed clean hands techniques (Stephenson, 2000a). Aqueous raw and filtered total mercury concentrations were measured by the California Department of Fish & Game at Moss Landing using a modification of EPA

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\(^4\) 20-23 mm shell length  
\(^5\) The panelling was manufactured by Plaskolite Inc. while the plastic mesh was purchased from Aquatic Eco-systems (www.aquaticeco.com)
method 1631 (Stephenson, 2000b). Aqueous raw and filtered methyl mercury concentrations were determined by Battelle Marine Sciences Laboratory using a modified EPA method 1631 (Battelle, 2000). TSS and VSS were analyzed by Sierra Foothill Laboratory using EPA methods 160.2 and 160.4, respectively. Chlorophyll and phaeophytin was measured spectrophotometrically by the California Department of Fish & Game (Strickland and Parsons, 1968). Water quality values obtained at the beginning and end of each month were averaged to estimate the mean concentration experienced by clams at a site during the month.

**Methyl Mercury Tissue Concentration and Individual Clam Weight and Mercury Burden**

Methyl-mercury tissue concentrations in clams and fish were determined by the California Department of Fish and Game using a flow injection mercury system (Stephenson, 2000a). Dry tissue weight per individual clam (gm-clam⁻¹) was estimated by dividing the composite weight of each sample by the number of clams comprising it. Methyl mercury burden is defined as the mass of methyl mercury per individual animal (ng methyl mercury clam⁻¹). Burden was estimated by multiplying the calculated weight of an individual clam by the average tissue concentration of the sample from which it was taken.

**Quality Assurance/Quality Control Program**

A laboratory quality assurance-quality control program was included to assess the accuracy and precision of the methyl-mercury tissue measurements. Accuracy was assessed two ways. First, a sample of a National Bureau of Standard certified reference material (marine bivalve *Mytilus edulis*, SRM 2976) was included with each set of clam tissue measurements. Second, with each set of mercury analysis, a randomly selected composite clam sample was spiked with a known amount of methyl mercury and reanalyzed. Precision was assessed by randomly selecting from each batch of clam tissue measurements one sample for reanalysis.

**Statistics**

Seasonal changes in clam methyl-mercury tissue concentrations were analyzed by ANOVA with Microsoft Excel. Statistical differences between means were assessed by a Dunnett’s mean separation test when the ANOVA suggested that statistically significant differences might exist. A probability value of 0.01 was employed (Zar, 1984).

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7 Sierra Foothill Laboratory, 823 S HWY 49, Jackson, CA, 95827.
Results

Quality Assurance-Quality Control Program

The accuracy and precision of the methyl mercury tissue data was assessed throughout the study and found to be acceptable. Accuracy was measured two ways. First, an analysis of a National Bureau of Standard’s *Mytilus edulis* reference material sample was included with each batch of composite clam tissue samples. Mean percent recovery in the 19 analyses was 95 percent (Table 1 in Appendix A). Second, randomly selected clam tissue samples were spiked with methyl mercury and the percent recovery of the spiked material measured. The average percent recovery in 18 spiked samples was 92 percent (Table 2 in Appendix A). Both the Standard Reference Material and the spiking studies suggest that the average methyl mercury tissue values reported here are biased low by about 5-8 percent. Laboratory precision was assessed by the repeated measurement of methyl mercury in randomly selected composite clam samples. The average relative percent difference\(^8\) between the 23 paired measurements was 9 percent (Table 3 in Appendix A).

Clam versus Fish Methyl Mercury Tissue Concentrations

A positive correlation was observed in 1999 between methyl mercury tissue concentrations in several common fish species and the Asiatic clam in the Bay-Delta Estuary. However, the sample size in many of the comparisons was small. Therefore, additional fishing was conducted in the fall of 2000 with an emphasis on largemouth bass. Other species were also taken when present in sufficient numbers. Purpose of the sampling was to ascertain whether a positive correlation would be maintained with larger sample sizes in a second year.

A positive relationship was again observed between methyl mercury concentrations in largemouth bass and in clams when combining the 1999 and 2000 data (P<0.0001, Table 1). A positive correlation was also present, although sample sizes were small, between Asiatic clams and Redear sunfish, Sacramento suckers, and Inland silversides (P<0.05, Table 1). The results suggest that the clam may serve as a proxy for methyl mercury concentrations in a number of common forage and game fish in the Estuary.

Results from samples collected in tributaries appeared as outliers in many of the clam-fish correlations. A sufficiently large clam-largemouth bass sample size was available from the tributaries and from the Delta to analyze the two separately. There was no correlation in tissue concentration between clams and largemouth bass inhabiting the tributaries (n=11, P=0.5, Table 2).

\(^8\)(High-Low)/(Mean of High and Low) X 100
**Clam Size versus Methyl Mercury Tissue Concentration**

Several hundred clams were collected from the Sacramento River at Rio Vista and from Putah Creek at Davis, sorted into 5-mm size classes, and analyzed to determine their methyl mercury tissue concentration. Purpose of the control experiment was to ascertain whether tissue concentration changed as a function of clam size. No relationship between size and concentration was observed at either location (Figure 3, $P>0.25$) suggesting that body size need not be closely controlled in selecting clams for transplant experiments or for comparison with fish tissue concentrations.

**Comparison of Caged and Wild Clam Tissue Concentrations**

A second control experiment was conducted to ascertain whether caged clams would demonstrate similar methyl-mercury tissue concentrations as wild animals from the same location. Several hundred clams were collected from both Putah Creek at Davis and from the Sacramento River at Rio Vista and placed into replicate cages at the location where collected. Eight to ten clams were harvested monthly from each cage, composited into a single sample per cage and analyzed for methyl-mercury. Also, wild clams were collected monthly and divided into three replicates for similar analyses. The results are summarized in Table 3.

A two-way ANOVA was run on the data from each location to ascertain whether differences existed in the tissue concentration of wild and caged animals. No difference was observed between wild and caged clams at either location during the ten-month exposure ($P>0.10$). However, seasonal differences were detected at both sites ($P<0.001$). Therefore, the wild and caged clam tissue data from each location was combined and three months of additional wild clam data included and a second ANOVA conducted.

The results demonstrate that clam tissue concentrations in Putah Creek were seasonally more variable than those of animals from the Sacramento River at Rio Vista (Figure 4). The concentrations in Putah Creek declined after September and reached a low in January of about half the pre transplant value. Concentrations remained low through April before increasing to a maximum in July where they remained until the end of the study. Tissue concentrations at the beginning (September 2000) and (September and October of 2001) of the study were similar suggesting that clams from Putah Creek may undergo a predictable seasonal methyl mercury tissue concentration pattern.

Methyl-mercury tissue concentrations in clams from the Sacramento River at Rio Vista were less variable (Figure 4). Concentrations were similar through the fall and winter but declined about 35 percent in spring to an annual low in April. Thereafter, the concentrations fluctuated back and forth between the values recorded the previous winter and those observed in April. Tissue concentrations measured in October 2001 were the same as those observed in September and October of the previous year suggesting that clams in the Sacramento River may, like those in Putah Creek, undergo a reoccurring, seasonal methyl mercury tissue concentration pattern.
In conclusion, clams from both Putah Creek at Davis and from the Sacramento River at Rio Vista demonstrated unique seasonal methyl-mercury tissue concentration cycles that included periods with statistically significant uptake and depuration. Caged clams at both locations consistently tracked the seasonal uptake and depuration cycle of the surrounding wild population suggesting that caged individuals could be used as surrogates for monitoring seasonal methyl mercury concentration changes in the wild population.

**Methyl Mercury Uptake and Depuration in Transplanted Clams**

A third control experiment was conducted to ascertain the rate at which caged clams could adjust their methyl mercury tissue concentration to that of the surrounding wild population. Clams from Putah Creek had 2.5 times more methyl mercury in their tissue in September 2000 than did animals from the Sacramento River (Figure 3, P<0.001, paired T-Test). Also, studies by Slotton et al. (2002) suggested that the tissue difference was as great as might be expected between clams from any two locations in the estuary. So, several hundred clams from Putah Creek were transplanted to cages in the Sacramento River at Rio Vista to evaluate their rate of methyl mercury depuration (high to low methyl mercury environment). Individuals from Putah Creek took two months to lose half their tissue concentration and become similar to wild Rio Vista animals (Figure 5). About 90 percent of the depuration occurred within the first 30 days. After two months, wild and caged clam tissue levels were similar and remained so for the remaining six months of joint exposure.

The second half of the reciprocal transplant consisted of moving clams from the Sacramento River at Rio Vista to Putah Creek (low to high methyl mercury environment) to determine the potential rate of methyl mercury uptake. Putah Creek clams were, as was explained previously but not known at the time of the transplant, in the process of depurating methyl mercury. Rio Vista clams transplanted to Putah Creek maintained a constant tissue concentration (Figure 6) while wild Putah clams decreased in mercury concentration. By January both had similar concentrations whereupon the two groups remained the same for the remainder of the 4-month study.

In conclusion, the reciprocal clam transplant study suggested that in the two cases examined, transplanted animals took two to four months to adjust their methyl mercury tissue concentration to that of the surrounding wild population.
**Change in Methyl Mercury Tissue Concentration**

The methyl mercury tissue concentration of any individual clam can be expressed from equation 1 as:

\[
\text{Tissue Concentration}_{T=2} = \text{Tissue Concentration}_{T=1} + \frac{\Delta \text{Methyl Mercury}_{T=1 \rightarrow T=2}}{\Delta \text{Dry Tissue Weight}_{T=1 \rightarrow T=2}}
\]

where tissue concentration \( T=1 \) and \( T=2 \) is the tissue concentration (ng gm\(^{-1}\)) of an individual clam at time 1 and 2, \( \Delta \text{Dry Tissue Weight}_{T=1 \rightarrow T=2} \) is the change in tissue weight (gm clam\(^{-1}\)) of an individual between time 1 and 2, and \( \Delta \text{Methyl Mercury}_{T=1 \rightarrow T=2} \) is the change in an individual clam’s mercury body burden (ng clam\(^{-1}\)) over the same time interval. An individual clam’s tissue weight was estimated by dividing the weight of the composite sample by the number of clams comprising it while methyl mercury body burden was calculated by multiplying the methyl mercury concentration of the composite sample by the weight of an individual clam.

An advantage of caging is that it is possible to follow a cohort of clams through time at any location and determine seasonal changes in methyl mercury body burden and tissue weight and ascertain how the two processes combine to produce a change in tissue concentration.

The methyl mercury concentration of clams collected from and transplanted back into cages at Putah Creek is presented in Figure 7a. The seasonal methyl-mercury tissue concentration pattern is similar to that presented previously in Table 3. Seasonal changes in methyl-mercury body burden and in tissue weight for the same clams are presented in Figure 7b. Both individual clam tissue weight and methyl-mercury burden decreased in September 2000. However, clams lost more methyl mercury than tissue weight resulting in a net decline in methyl mercury tissue concentration. Methyl mercury body burden was relatively stable between October 2000 and April 2001 while tissue weight increased slowly from 0.4 to 0.6-gm between October and February and then rapidly in March to 0.9-gm before declining again to 0.6-gm in April. Thereafter, both tissue weight and methyl mercury body burden increased simultaneously but incorporation of methyl mercury occurred more rapidly than tissue weight resulting in a net doubling in methyl-mercury tissue concentration (Figure 7a).

The methyl mercury tissue concentration of clams collected from and transplanted back to cages in the Sacramento River at Rio Vista is presented in Figure 8a. The data was, like at Putah Creek, used to determine the monthly change in tissue weight and methyl mercury body burden of caged River clams (8b). Methyl mercury and tissue weight decreased slightly in the fall, was relatively stable through the winter until March 2001 whereupon tissue weight increased from 0.6 gm to 1.1 gm in April, stabilized for a month then continued to increase. Methyl mercury body burden commenced increasing a month later in the spring than did tissue weight, declined slightly in May and continued to climb in June. The net result was a reasonably stable methyl-mercury tissue concentration.
between September and February followed by a decline in March that persisted through July (Figure 8b).

As noted previously, seasonal changes in methyl-mercury tissue concentration in the Sacramento River and in Putah Creek clams appear very different (Figure 4). Yet, several similarities emerge when the underlying processes of change in tissue weight and methyl mercury body burden are examined (Figures 7b and 8b). First, clams at both locations decreased in weight and in body burden in September and again in April-May. Second, both groups exhibited relatively stable weight and body burdens during winter and early spring (October-February). Finally, tissue weight and methyl mercury-body burden increased at both sites in spring. Tissue weight began to rise at both locations in March while methyl mercury uptake at Rio Vista commenced in April and at Putah Creek in May. The difference in methyl mercury tissue concentrations at the two sites results from the relatively greater changes in methyl mercury than in weight at Putah Creek in both the fall and spring.

_Corbicula_ is a marsupial bivalve and incubates its young on its inner gill. Reproduction occurs in April-May and again in August-September (Eng, 1979; Foe and Knight, 1981). About 10 wild and caged clams from Putah Creek and from the Sacramento River were examined monthly in September 2000 and in again in April and May 2001 to determine their reproductive state. About half the wild and caged clams from Putah Creek contained trochophore larvae in their gills in both September and April, though the wild clam population appeared to reproduce more strongly than did the caged one. Similarly, gill tissue from Rio Vista demonstrated that clams spawned in September and again in April-May. This undoubtedly explains the weight loss in both the Creek and River during late fall and again in spring and may also explain the simultaneous decline in methyl mercury body burden. However, control experiments are needed to confirm the importance of reproduction in clam methyl mercury depuration.

**Comparison of Change in Clam Methyl Mercury Body Burden and Aqueous Mercury Concentrations**

A hypothesis at the beginning of the CALFED Mercury Mass Load Study (Foe, 2002) was that there was a positive relationship between aqueous mercury concentration and methyl mercury uptake in biota. Seasonal changes in raw and filtered total and methyl mercury are plotted for the Sacramento River water at Greene Landing (10 miles upstream of Rio Vista) and for Putah Creek against changes in the methyl mercury body burden of individual clams from both sites in Figures 9 and 10. While the data set is small, there does not appear to be an obvious relationship between any of the four forms of aqueous mercury and seasonal changes in clam body burden levels. In particular, the large concentrations of unfiltered total and methyl mercury in Putah Creek and in the Sacramento River in winter and in early spring (March to April) do not result in an increase in clam methyl mercury body burdens at either location. Conversely, the large increase in clam methyl mercury body burden at both sites in May and June was not associated with a discernible increase in aqueous mercury concentrations.
**Second Clam Transplant**

Four thousand clams were transplanted to 11 locations around the Bay-Delta Estuary in March 2001. Purpose of the transplant was threefold. First, ascertain whether the caging technique could be employed in other aquatic environments including large valley rivers. Second, determine how methyl mercury tissue concentration changed seasonally in the different environments and, finally, if possible, determine water quality constituents responsible for changes in clam methyl-mercury tissue concentrations.

**Cage Performance**

Two or more cages were lost at 5 of the 11 sites during the seven-month exposure resulting in the termination of the study at those locations. The reason for the loss of the cages was not always clear. While not a wet year, the Sacramento River at Colusa and the Feather River at Nicholas rose more than 20 feet after the cages were transplanted. Two cages at Colusa and one at Nicholas were lost during the high flow, possibly because the cages became entangled with floating trees. Clams in the remaining two cages at Nicholas were smothered beneath a sand-wave in May. The cages at Franks Tract disappeared; they may have been found and removed by fishermen. The State Water Project’s Bethany Reservoir was drained because of a canal leak resulting in the clams becoming exposed and dying. Finally, salinity at Mud Slough rose above the clam’s osmotic tolerance (3-5 o/oo) killing them.

Clam cage mortality at the remaining sites around the estuary averaged 5-6 percent for the seven-month exposure. About half the death occurred during the first month. Only clam tissue data from the six surviving sites (Figure 1) has been used in the subsequent analysis.

**Methyl-Mercury Tissue Concentrations**

An unexpected finding of the second transplant was the large amount of temporal and spatial variation in clam methyl-mercury tissue concentrations in the estuary (Figure 11). For example, clams transplanted to the Mokelumne River and to Cache Creek doubled their concentration while animals planted in the San Joaquin River decreased theirs by a factor of three. Also, there did not appear to be a consistent seasonal pattern in the tissue changes. For example, methyl mercury concentrations in clams from Cache Creek were highest in April and May, in the Mokelumne River in June and July and in the Sacramento River in October. Finally, the concentration in clams from Prospect and Georgiana Sloughs remained relatively similar throughout the study.

The monthly change in weight and in methyl mercury body burden of individual clams from each site was calculated to determine whether either might explain the variable nature of clam tissue concentrations around the estuary.
**Tissue Weight**

Clam weight gain was relatively similar at all sites during the 7-month exposure (Figure 12). Bivalves increased in weight from 0.6 to 1.4-1.7-gms between March and October 2001. The exception was clams from the San Joaquin River at Vernalis. These animals grew from 0.6 to 2.6 gm-dry weight during the 7-month study.

The interpretation of the weight gain data is complicated by the fact that reproductively active animals were transplanted. *Corbicula* first reproduces at about 10-12 mm (Aldridge and McMahon, 1978). Great effort was expended prior to the second transplant to locate a site with sufficient numbers of juvenile clams for the study. No such location was found. So, reproductively active animals were used. No attempt was made during the second transplant to ascertain whether caged animals reproduced at any site as no wild clams were available at most of the locations for examination and the cages contained an insufficient numbers of animals to sacrifice any for histological observations. However, tissue weight loses strongly suggested that clams from Cache Creek and from Georgiana Slough reproduced in May and animals from all other sites, except the San Joaquin River at Vernalis, reproduced in July (Figure 12). Sufficient food may have been available in the San Joaquin River for animals to grow and reproduce simultaneously.

The growth of *Corbicula* is strongly influenced by water temperature and food. Laboratory scope-for-growth studies demonstrate that the clam’s growth potential is greatest between 16 and 24°C and declines at higher temperatures (Foe and Knight, 1987). The laboratory scope for growth studies were conducted under conditions of unlimited food. Field studies document that the Asiatic clam is food limited most of the year in the Sacramento-San Joaquin Delta (Foe and Knight, 1985) suggesting that field growth is a function of water temperature and available food (chlorophyll and phaeophytin).

Clam tissue growth in the present study was evaluated as a function of available food (chlorophyll and phaeophytin) and temperature (Figure 13). The analysis was conducted after removing all data for months when the clams were believed to have reproduced and all Vernalis data obtained after July 2001. The Vernalis data was not included as clams became larger than the size of their cage compartments and this may have restricted growth. A correlation was run using tissue growth as the dependent variable and food as the independent one after separating the growth data into months with water temperatures less than and greater than 22°C. The two correlations explained 46 to 49 percent of the variance (P<0.01) and confirmed the importance of temperature and food in regulating clam growth. A potential problem with the present study is that chlorophyll and temperature at most locations are more variable than can be captured with a single measurement every 30 days. As such, estimates for each location can only be considered as *indices* of available food and temperature.
**Methyl Mercury**

Clams transplanted to all sites, except the Mokelumne River, demonstrated similar seasonal methyl mercury body burden patterns (Figure 12). Almost all the mercury uptake occurred between March and June whereupon body burdens became stable or declined slightly. These results are consistent with the findings of the first transplant study at Putah Creek and Rio Vista. Methyl mercury burden was constant all winter and spring and then increased rapidly after April and May in both the Creek and River (Figure 7b and 8b). Together the results suggest that much of the annual uptake of methyl mercury occurred in the 4-month time interval between March and June. Clams from the Mokelumne River were different and showed a high uptake rate between March and May and depuration in July.

The amount of methyl mercury incorporated into the clams in the 4-month spring time interval was variable by site. Pre transplanted clams contained about 60-ng methyl mercury per individual. By July the mercury content of individual clams varied from 90 to 325 ng. This is a 0.5 to 4.4-fold increase. In contrast, tissue weights increased from 0.6-gms to 1.4 to 1.8-gms during the same time interval, equivalent to a 1.4 to 1.8-fold increase in weight. The much smaller and less variable increase in weight is consistent with the observations at Putah Creek and at the Sacramento River at Rio Vista (Figure 7b and 8b) and emphasizes the importance of site-specific methyl-mercury uptake rates in determining clam methyl mercury tissue concentrations.

The rate of change in methyl mercury body burden per month (ng methyl mercury-clam\(^{-1}\) month\(^{-1}\)) was regressed against a suite of water quality parameters to determine whether any might be correlated with the change in clam body burden (Table 4). A correlation was run for all the data (uptake and depuration) and just uptake (positive change in methyl mercury). Significant relationships were observed between change in body burden and raw and filtered aqueous methyl mercury concentrations divided by all measurements of available food (chlorophyll, chlorophyll + phaeophytin, TSS, VSS). However, the relationship was stronger when only the uptake data was used. This may be because uptake and depuration are the result of different physiological processes and most of the data (32 of 42 values) was only for uptake. Also, stronger relationships were observed when direct measures of algal biomass (chlorophyll or chlorophyll + phaeophytin) were used. The strongest relationships accounted for 42 percent of the variance and had an associated P-value of 6 X 10\(^{−5}\) (Figure 14).

Methyl mercury tissue concentrations are a function of methyl mercury uptake divided by tissue growth (equation 1). Field data demonstrates that methyl mercury uptake is a function of ambient methyl mercury/chlorophyll + phaeophytin concentration while tissue growth is a function of chlorophyll + phaeophytin (Figures 13 and 14). Substituting both terms into equation 1 and simplifying results in:
\[ \Delta \text{Tissue Concentration} = \frac{(\text{Methyl Mercury Concentration})}{(\text{Chlorophyll + Phaeophytin Concentration})^2} \]

Equation 2 predicts that change in clam methyl-mercury tissue concentration is controlled by ambient methyl mercury and chlorophyll concentrations.
DISCUSSION

The primary objective of the clam transplant study was to measure the uptake of methyl mercury in the food web of the Bay Delta Estuary and, if possible, determine factors controlling it. The single largest and most variable step in the accumulation of methyl mercury in aquatic food chains is the transfer of the substance from water to phytoplankton (Watras and Bloom, 1992; Ploude et al., 1997; Paterson et al., 1998; Watras et al., 1998; Bowles et al., 2001). Phytoplankton is microscopic and our knowledge about mercury concentrations in primary producers is based upon measurements of seston and of filter-feeding organisms consuming it. By definition, seston includes all particles suspended in the water column larger than 0.45 µ. This includes, in addition to phytoplankton, other inorganic and organic matter of varying nutritional value and differing affinity for methyl mercury. Particles are handled differently by filterfeeders based on size, density, and nutritional value (Jorgensen, 1966; Bayne et al., 1976a) making it difficult, a priori, to predict the methyl mercury exposure experienced by a primary consumer based solely on unfiltered methyl mercury concentrations. The present study employed the filter-feeding clam, *Corbicula*, to monitor the bioavailability of unfiltered methyl mercury concentrations at different locations in the Bay-Delta Estuary and its tributaries.

Control Experiments

Three experiments were undertaken to help interpret the results of the clam transplant experiments. First, composite samples of clams and several common fish species were collected to ascertain whether invertebrate and fish species exhibited similar tissue concentration patterns. The emphasis was on largemouth bass, a widespread and common sportfish. A positive correlation was observed in methyl mercury tissue concentrations between bass and the Asiatic clam (P<0.0001, Table 1). Although sample sizes were smaller, positive relationships also existed between clams and four of the nine other fish species examined (Table 1). The results are consistent with the conclusions of Slotton et al (2000) and Davis et al (2002) that many species in the Bay-Delta aquatic community exhibit similar spatial methyl mercury tissue patterns. The results also suggest that the clam might serve as a model for attempting to understand methyl mercury uptake in the estuary food web.

No correlation existed between largemouth bass and clams collected in rivers tributary to the Delta (Table 2). There are at least two possible explanations. First, the tributary food web might be different than the Delta and the clam may not be as good a surrogate for methyl mercury uptake. Alternatively, this study found significantly more methyl mercury depuration in clams collected from tributaries than from the estuary. For example, methyl mercury-tissue concentrations in clams from Putah Creek and from the Mokelumne River varied 2.5 to 3.5-fold over the course of a summer (Figure 7 and 11). In contrast, clams from the Estuary, like the Sacramento River at Greene Landing or at Rio Vista, only varied in tissue concentration by 50 percent during the same time period (Figure 8 and 11). A fundamental assumption in collecting clams and fish at the end of the summer is that their tissue concentrations represent the sum of all the methyl mercury
entering the animal during the year. This is likely true for fish which have relatively long methyl mercury half lives but not so for clams which can depurate methyl mercury more rapidly. The faster cycling of methyl mercury in clams decreases their utility as long-term integrators of methyl mercury uptake from the base of the food chain.

It is important to note that while clams are the most common benthic invertebrate in many Central Valley rivers and in the freshwater side of the estuary (biomass), they are seldom observed in the guts of fish (reference?). Therefore, clams are not likely to be an important dietary element in the transfer of methyl mercury in the aquatic food web. Instead, the strong correlation between clams and fish probably result from the fact that the clam is a surrogate for other filter feeders, like zooplankton, which are important in the Delta pelagic food web.

Several control experiments were undertaken to determine whether caged clams could be used as surrogates for the wild clam population upon which the fish tissue correlations were based. The purpose of the first control experiment was to establish whether caged and wild clams exhibited the same seasonal methyl mercury tissue pattern. The tissue concentration of caged and wild clams in Putah Creek and in the Sacramento River at Rio Vista was similar for the ten-month study (P>0.25). The conclusion is particularly robust at Putah Creek as wild and caged clams lost half their methyl mercury (going from 240 to 142 ppb) and recovered it during the study. A second control experiment was undertaken to determine the potential rate of methyl mercury uptake and depuration in *Corbicula*. Clams were transplanted from the Sacramento River to Putah Creek (low to high methyl mercury environment) and vice versa. Clams in the reciprocal transplant took two and four months, respectively, to become similar to the wild population whereupon the concentrations of both groups remained similar for the remainder of the experiment (Figure 5 and 6). In conclusion, control experiments suggested that transplanted caged clams could be used as a surrogate for the wild population if held for at least four months.

An unexpected finding of the initial clam transplant study was the high rate of methyl mercury depuration. Clams transplanted from Putah Creek to the Sacramento River decreased their methyl mercury content in half within 30 days (Figure 5). Clams caged in the Mokelumne River did the same in July 2001 (Figure 11). In contrast, the half-life of methyl mercury in fish is on the order of a year (McKim *et al.*, 1976;Burrows and Krenkel, 1973). The result suggests that methyl mercury is either stored or metabolized differently in freshwater molluscs than in fish. The timing of depuration often appeared to co-occur with reproduction.

Clams of varying size were collected from the Sacramento River at Rio Vista and from Putah Creek in September 2000, sorted into 5-mm size classes, and analyzed for methyl mercury. Mercury concentrations were found to be independent of clam size (and age) (Figure 3, P>0.25). This result was unexpected as similar analyses in fish consistently demonstrate that methyl-mercury tissue concentrations increase with body length (Davis *et al.*, 2002;Wiener and Spry, 1996). The increase in fish is hypothesized to occur because the rate of methyl mercury uptake is faster than depuration resulting in a net increase in tissue concentration over time. In contrast, the rate of methyl mercury uptake
and depuration is similar in *Corbicula*\(^9\) and may explain why methyl mercury tissue concentrations are independent of clam size.

**Methyl Mercury Tissue Concentrations**

One of the main objectives of the study was to determine the temporal and spatial pattern of methyl mercury-tissue concentrations in the Bay-Delta Estuary. Clam tissue concentrations are important because they indicate the amount of methyl mercury per unit organic matter being transferred from the base of the food chain to higher trophic levels. Two studies were undertaken to measure tissue concentration changes. The first was a one-year study (September 2000-September 2001) in Putah Creek and in the Sacramento River at Rio Vista (Figure 4, Table 3). The second was a seven-month study at six locations in and around the Estuary (February and October 2001, Figure 11).

Four important findings emerge from the two studies. First, as noted previously, tissue concentrations were often higher in mercury contaminated tributaries than in the estuary. For example, clams from Putah and Cache Creeks and from the Mokelumne-Consumnes Rivers (Figure 4 and 11) had higher methyl mercury tissue concentrations than did clams from the Sacramento River at either Rio Vista or Greene Landing. A possible explanation for higher tributary tissue concentrations is that aqueous raw methyl concentrations were also highest there (Foe, 2002). Insufficient data was collected to evaluate the system wide pattern in chlorophyll during the study. However, the historical pattern is for chlorophyll concentrations to be lower in the tributaries, except the San Joaquin, and increase through the Delta (Lehman, 1996). Higher concentrations of unfiltered methyl mercury coupled with lower chlorophyll concentrations are predicted to result in a higher tissue value (Equation 2) as was observed.

A second finding was the lack of bioavailability of the high aqueous methyl mercury concentrations in winter. Clam tissue concentrations were followed at Putah Creek and at the Sacramento River at Rio Vista during the winter of 2000-2001. Tissue concentrations were constant at both locations between January and April while raw methyl mercury concentrations were at annual maxima (Figure 9 and 10; Foe, 2002). The clam is metabolically inactive in winter at the low temperature characteristic of the Central Valley (Foe and Knight, 1987). The reduction in filtration and assimilation rate may explain the reduced bioavailability of mercury.

Another important finding was that there appeared to be an annual methyl-mercury-tissue concentration cycle in clams at both Putah Creek and at the Sacramento River at Rio Vista. Tissue concentrations were followed at both locations for one year and the concentration at the beginning (September) and end of the study was similar at both locations (Figure 4). The presence of a seasonal cycle was particularly convincing at Putah Creek where clams lost and gained back about 60 percent of their tissue concentration during the year.

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\(^9\) For example, clams transplanted to the Mokelumne River doubled and halved their methyl mercury body burden in 30 days (Figure 12).
The last finding was that there was no consistent seasonal methyl mercury-tissue pattern in the Delta or its tributaries. Increases in methyl mercury were measured in March on Cache Creek; in April on the Mokelumne-Consumnes Rivers, Putah Creek, and the Sacramento River at Greene Landing; in June on Putah Creek and the Sacramento River; and in July on Putah Creek (P<0.01, Figure 11). In contrast, depuration occurred in March on both the Sacramento River at Greene Landing and the San Joaquin River at Vernalis; in April on Cache Creek; in May on the Mokelumne-Consumnes Rivers and in July on Putah Creek. No difference in tissue concentration was measured during the seven-month exposure at Georgiana or Prospect Sloughs or the Sacramento River at Rio Vista (P>0.1, Figures 8 and 11). In conclusion, the seasonal change in methyl mercury tissue concentrations in clams is unpredictable from one location to the next in the Delta and its tributaries.

**Factors Controlling Methyl Mercury Tissue Concentration**

Caged clams were used to measure changes in methyl mercury tissue concentration as a function of changes in body burden (ng methyl mercury-clam⁻¹ month⁻¹) and tissue growth (gm-dry weight month⁻¹) using procedures outlined in (Beckvar et al., 2000; Sundra and Huntsman, 1998). Unequal assimilation of either methyl mercury or carbon will result in a change in tissue concentration (equation 1). From a management standpoint, methyl mercury-tissue concentration can either be minimized by decreasing the rate of methyl mercury uptake or by increasing carbon assimilation in the food chain.

Invertebrate tissue growth is a well studied phenomena and is influenced, among other things, by the quantity and quality of available food, temperature, reproductive state, salinity and disease (Jorgensen 1966; Seed, 1976; Bayne et al., 1976b). In this study clam growth was found to be a function of chlorophyll, temperature and reproduction. Increasing chlorophyll concentrations and water temperatures between 16 and 22°C resulted in positive tissue growth (Figure 13) while low winter temperatures (9-13°C) suppressed it. *Corbicula* reproduces in April-May and August-September and these time periods were often associated with weight loss, though active reproduction was only verified in Putah Creek and in the Sacramento River at Rio Vista in the fall of 2000 and the spring of 2001.

Tissue growth appeared relatively predictable at the seven locations monitored around the estuary in the spring and summer of 2001 (Figure 12). Clams increased in weight from 0.6 to 1.4-1.7-gm individual⁻¹, a 1.3-1.8-fold weight gain. Most of this increase occurred between March and June and appeared to coincide with an increase in both water temperature and chlorophyll concentration. Weight loses were less predictable, but if present, occurred most often in April-May and in September, coincident with possible reproduction. The effect of tissue growth on mercury concentrations has been termed *biodilution* (Sunda and Huntsman, 1998) but the term is misleading as growth can either be positive or negative and this may result in either an increase or decrease in methyl mercury tissue concentration.
Factors controlling methyl mercury uptake in herbivorous filter feeders are not well understood. Pickhardt et al. (2002) demonstrated that methyl mercury uptake in *Daphnia* was a function of raw aqueous methyl mercury concentration divided by chlorophyll. The authors hypothesized that *Daphnia* feeding rates were finite and most of the mercury was attached to algal cells in their laboratory study. Increasing algal biomass reduced mercury accumulation by diluting the mass of mercury per algal cell consumed. The present study found that methyl mercury uptake in caged clams was also best described as a function of raw aqueous methyl mercury divided by chlorophyll and phaeophytin concentration (Table 4, Figure 14). Most of the methyl mercury uptake, as with tissue growth, occurred between March and June (Figure 12). The rate of methyl mercury uptake around the estuary was more variable than tissue growth. The initial body burden of transplanted clams was 60-ng methyl mercury individual$^{-1}$ and increased during the seven-month clam exposure to between 95 and 330 ng mercury individual$^{-1}$, a 0.6 to 4.5-fold increase. This contrasts with a 1.3 to 1.8-fold increase in tissue weight during the same time period and emphasizes the importance of methyl mercury uptake in determining tissue concentrations.

**Conceptual Model**

The results of the pilot clam transplant study suggest a conceptual model of methyl mercury accumulation at the base of the Bay-Delta food chain (Figure 15). At least three biological processes appear important in governing tissue concentrations. These are the chlorophyll cycle, the physiology and ecology of primary consumers in the aquatic community, and the methyl mercury cycle.

The life history of many members of the Bay-Delta aquatic community appear synchronized to the phytoplankton cycle. Primary production is the source of the carbon and nitrogen in the food chain. Simultaneously, algal cell density acts to keep methyl-mercury tissue concentrations low in aquatic life. The latter is because algal biomass, as measured by chlorophyll and phaeophytin, is the divisor term in equation 2. The historical chlorophyll pattern, although somewhat variable through the system, is for concentrations to be low in fall and winter (October to March) and increase rapidly in the spring with rising temperature and solar radiation (Lehman, 1996). The highest algal concentrations occur between April and June in the Delta and gradually decline as summer progresses. Clam growth was highest at most sites between April and June (Figure 12) as would be expected from the strong correlation between tissue growth and chlorophyll concentration (Figure 13). Zooplankton density (copepods, cladocerans and mysids) also has an annual maxima at this time, coincident with increases in available food (personal communication Dege;Department of Water Resources, 2001). Finally, many resident fish spawn between April and June (Table 5). An advantage of this spawning schedule is that it places fish larvae in the water at the same time as the highest zooplankton concentrations of the year. In conclusion, spring and early summer is a critical period in the Delta for maximum carbon synthesis by algae and for tissue accretion in clams, zooplankton and fish populations.
Aqueous methyl mercury concentrations result from the synthesis of organic mercury by sulfate reducing bacteria in sediment and its demethylation by a combination of biotic and abiotic processes in both water and sediment (Marvin-DiPasquale and Agee, 2002). The fact that methyl mercury is always detectable in the Estuary implies that synthesis is greater than demethylation. The timing and magnitude of net methyl mercury production in the Delta and its tributaries is now being studied for the first time (Marvin-DiPasquale and Agee, 2002, Gill et al., 2002, Heim et al., 2002). Methyl mercury concentrations on the Sacramento River, the largest source of methyl mercury to the Bay-Delta Estuary, was highest between January and May in both 2000 and 2001 (Foe, 2002). No seasonal pattern was noted for any other river input. In contrast, most of the methyl mercury uptake by clams occurred somewhat later, between April and June (Figure 12) coincident with maximal clam tissue growth. Elevated methyl mercury tissue concentrations, not high uptake rates per se, are hazardous to aquatic life. Equation 2 predicts that tissue concentrations are a function of the unfiltered methyl mercury concentration divided by the square of the chlorophyll concentration. Therefore, if the photosynthesis cycle is synchronized with the methyl-mercury one, as generally occurred in the Delta in 2001, then elevated methyl mercury tissue concentrations do not result. In contrast, methyl mercury concentrations were higher in most of the tributaries than in the estuary in spring and early summer while chlorophyll concentrations were lower (Foe 2002). The result was higher tributary methyl mercury tissue concentrations in both clams and in fish (Slotton et al., 2002; Davis et al., 2002).

Finally, the ecology and physiology of the principal filter feeding herbivores in the Bay Delta are important. Filter feeders are critical as they harvest algae. Algae are, as previously mentioned, the principal biomagnification step in the aquatic food chain. Primary consumers must be present in large numbers and be metabolically active to efficiently harvest the methyl mercury when present at elevated levels. Zooplankton densities are greatest in the Delta in spring and early summer. Corbicula is long lived and present all year but only has high filtration and assimilation rates at the warmer water temperature characteristic of late spring and early summer. As a result the clam (and presumably the zooplankton community) are able to efficiently capture methyl mercury then. In contrast, Corbicula was not metabolically active in winter in Putah Creek and in the Sacramento River and unable to assimilate a measurable amount of the high methyl mercury concentration present. It is not known whether any other filter feeder was present in sufficient density and had a high enough metabolic rate to capture the material or whether the chemical flushed harmlessly through the Delta to the Pacific Ocean.

In conclusion, methyl mercury tissue concentrations at the base of the food chain result from three processes: the primary production cycle, methyl mercury cycle, and physiology and ecology of the filter feeding community. Elevated methyl-mercury tissue concentrations result from the simultaneous occurrence of low phytoplankton concentrations, high methyl mercury concentrations and elevated metabolic rates in primary consumers. The timing and magnitude of these processes are somewhat different in each water body and this results in different methyl-mercury tissue concentration patterns in clams as was observed in the Delta and in its tributaries in 2001 (Figure 11).
Literature Cited


Table 1. Pierson correlation coefficients and associated probability value for methyl mercury tissue concentrations in composite fish and clam samples collected in the Sacramento-San Joaquin Delta Estuary and in its tributaries in 1999 and 2000. Statistically significant relationships are indicated in bold. Data for all species are in ppm wet weight except for Silversides and Asiatic clams which are dry weight.

<table>
<thead>
<tr>
<th></th>
<th>Striped Bass</th>
<th>White Catfish</th>
<th>Channel Catfish</th>
<th>Blue Gill</th>
<th>Redear Sunfish</th>
<th>Sacramento Suckers</th>
<th>Pike Minnow</th>
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Table 2. Pierson correlation coefficients for methyl mercury tissue concentration of composite Largemouth bass and Asiatic clam samples collected in the Bay-Delta Estuary and in its tributaries in 1999 and 2000. Statistically significant correlations are indicated in bold.

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<th>Delta</th>
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Table 3. Methyl mercury tissue concentration (ppb dry weight) in wild and caged clams from the Sacramento River at Rio Vista and from Putah Creek at Davis during 2000 and 2001. Values are the mean ± standard error of the composite of 8-10 clams from 3 cages at each site.

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<th>1 Sept</th>
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<th>1 July</th>
<th>1 Aug</th>
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1/ Pretransplant animals.
2/ Wild clams collected from and transplanted back into cages at Putah Creek.
3/ Wild clams collected from the Sacramento River at Rio Vista and transplanted into cages in Putah Creek.
4/ Wild clams from Putah Creek.
5/ Wild clams collected from and transplanted back into cages in the Sacramento River.
6/ Wild clams collected from Putah Creek and transplanted into cages in the Sacramento River.
7/ Wild clams collected from the Sacramento River at Rio Vista.
Table 4. Correlation between the rate of methyl mercury uptake and depuration in caged clams (ng/month) and the concentration of selected aqueous constituents during the same time period. The rate of change in methyl mercury was used as the dependent variable and constituent concentration as the independent one. Correlations evaluating all the data (uptake and depuration) are labelled “all” while relationships for just uptake are called “uptake”. NS denotes a non-significant result (P>0.05).

<table>
<thead>
<tr>
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<td>Filtered total Hg (ng/l)</td>
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Table 5. Spawning chart for common fish in the Sacramento-San Joaquin Delta Estuary.

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Note: Italized species name is non-native fish

Adapted from a chart developed by Jennifer Bull, CDFG - Bay Delta Division, 1994
Figure 1. Map of Clam Collection and Transplant Sites in the Sacramento-San Joaquin Bay-Delta Estuary.
Figure 2. Cages with and without clams enclosed.
Figure 3. Methyl mercury tissue concentration as a function of 5 mm shell length size classes in clams collected from Putah Creek at Davis and from the Sacramento River at Rio Vista in September 2000.
Figure 4. Seasonal methyl mercury tissue concentration in clams collected from Putah Creek at Davis and from the Sacramento River at Rio Vista in 2000 and 2001. Values in the same line with the same letter are not different (P<0.01)
Figure 5. Methyl mercury tissue concentrations of clams transplanted from Putah Creek to cages in the Sacramento River at Rio Vista and of wild clams from the Sacramento River. Values with the same letter are not different (P<0.01)
Figure 6. Methyl mercury tissue concentration tissue concentration of clams transplanted from Sacramento River at Rio Vista to cages in Putah Creek and of wild clams Putah Creek. Values with the same letter are not different (P<0.01).
Figure 7. (a) Methyl mercury concentration of caged clams in Putah Creek in 2000 and 2001. Values with the same letter are not different. (b) Average change in dry tissue weight and methyl mercury body burden of caged clams at Putah Creek.
Figure 8. (a) Methyl mercury concentration of caged clams in the Sacramento River at Rio Vista in 2000 and 2001. Values with the same letter are not different. (b) Average change in dry tissue weight and methyl mercury body burden of caged clams in the Sacramento River.
Figure 9. (a) Comparison of aqueous raw and filtered total mercury in Putah Creek and methyl mercury body burden of transplanted clams. (b) Same comparison with raw and filtered methyl mercury.
Figure 10. (a) Comparison of aqueous raw and filtered total mercury in the Sacramento River at Rio Vista against the methyl mercury content of individual clams. (b) Same comparison for raw and filtered methyl mercury.
Figure 11. Methyl mercury tissue concentration of clams transplanted around the Sacramento-San Joaquin Delta Estuary in 2001.
Figure 12. Seasonal changes in individual clam weight and methyl mercury body burden around the Estuary in 2001.
Figure 12 (continued)
Figure 13. Caged clam tissue growth in the Sacramento-San Joaquin Delta as a function of water temperature and phytoplankton concentration.
Figure 14. Change in transplanted clam methyl mercury body burden (ng/clam/mo) as a function of the raw methyl mercury concentration of the water divided by the sum of the chlorophyll and phaeophytin concentration.

\[ y = 907.4x + 10.383 \]

\[ R^2 = 0.42 \]
Figure 15. Conceptual model of important biological processes controlling methyl mercury uptake at the base of the Bay Delta Food Web.