

# A Comparison of Selenium and Mercury Concentrations in Transplanted and Resident Bivalves from North San Francisco Bay

Samuel N. Luoma and Regina Linville  
United States Geological Survey, Menlo Park

## Monitoring With Bioindicator Species

Many of the methodologies for effective use of organisms to monitor and study contamination in estuaries are well established (Phillips, 1980; Phillips and Rainbow, 1993). Understanding the processes that determine bioaccumulation and determining concentrations of contaminants in biological tissues are best employed in conjunction with analysis of other environmental media (e.g., water, suspended particulate material, or sediment). Together these provide complementary lines of field evidence indicative of complexities that affect the exposures of organisms to contaminants. While tissue analysis is not universally suitable as a measure of exposure for all contaminants in all organisms or all circumstances, it does have important advantages when properly used:

1. Concentrations in tissues may be more responsive to environmental contamination than concentrations in water and/or sediments in some circumstances, providing a unique perspective on understanding exposures.
2. Measurements of contaminant concentrations in organisms provide a time-averaged assessment. Temporal variability can be a problem in understanding contamination. However, temporal variability is moderated by biological processes in animal tissues compared to other environmental media; thus organisms are described as "integrators" of contamination.
3. Understanding bioaccumulated concentrations can provide a more direct measure of bioavailability than determination of concentrations in water or sediments. One of the important difficulties in understanding

the effects of pollutants in nature lies in understanding how biological and geochemical factors influence the dose that an organism experiences. Tissue concentrations of contaminants can be a direct measure of dose, and thus help reduce ambiguities in interpreting environmental exposures.

Results of tissue analyses are most sensitive to environmental contamination when the bioindicator species chosen for study is highly responsive to changes in contaminant exposure. Appropriate sample size (number of individuals; number of replicate analyses) and sample mass are crucial for interpretable results because variability can be large among individual organisms of the same species, especially in contaminated environments. Tissue, life stage, reproductive condition, size, sex, and gut content can be sources of variability and at least need to be considered. Probably most importantly, contaminant concentrations are directly comparable only within the same species, unless proven otherwise. Bioaccumulation of trace element contaminants can differ among even closely related species; although trends in time and space are often similar among species.

## Residents Versus Transplanted Organisms

Either resident populations or individuals transplanted from one environment to another can be employed to monitor and assess contaminant exposures, fate, distribution, or bioavailability. The California State Mussel Watch Program, the Regional Monitoring Program (RMP) and numerous specific studies (Smith *et al.*, 1986; Phillips, 1988; Rasmussen,

1994) have employed the transplant approach. In the RMP, bivalves are collected from sites thought to be uncontaminated and transplanted to San Francisco Bay. Tissue concentrations are determined at the beginning of the deployment and after a 90–100 day deployment period. Detailed methodologies for employing mussels (*Mytilus edulis*; *Mytilus californianus*) in transplant experiments are well developed (Phillips, 1988) and are described in the Background section of this chapter and in Appendix A.

An extensive literature is also available on the use of resident species as bioindicators (Phillips, 1980; Phillips and Rainbow, 1993; see also *The RMP Workshop on Ecological Indicators of Contaminant Effects*, this report). A suitable resident indicator species should be (1) widely distributed and abundant in the ecosystem(s) of interest; (2) feasible to collect in numbers suitable for statistical validity (>15–20 per collection); (3) sufficient in tissue mass that analysis is practical; (4) sufficiently tolerant to contaminants that the species will be present (i.e. survive) in at least moderately contaminated situations; and (5) sufficiently restricted in movement that values are representative of the location or region of interest.

The most important advantage of employing transplanted species is that the same species may be placed at any station whether or not the species is present naturally. A second advantage is that transplanted populations may provide a common baseline from which to evaluate contamination. The deployed organisms should have a common history of exposure to only low levels of contamination. Thus, tissue concentrations in transplanted organisms should reflect only changes in concentration that have occurred during the deployment period.

Some practical disadvantages can hinder the transplant approach. Changes in behavior of the transplanted organisms because of the deployment is always a consideration, although in the history of California Mussel Watch this does not seem to prevent evaluations of trends in space and time (Phillips, 1988; Rasmussen, 1994). Nevertheless it is difficult to determine if behavioral attributes important to bioaccumulation are similar in transplanted and native

organisms (i.e., if stress from deployment has affected results; Cain and Luoma, 1985). In estuaries the advantage of deploying a single species to all sites is partly countered by wide ranging and variable salinities. The RMP transplant approach does not solely use mussels in San Francisco Bay because the range of salinities is broad. The RMP employs mussels (*Mytilus californianus*), oysters (*Crassostrea gigas*), and freshwater/brackish water clams (*Corbicula fluminea*), respectively, in reaches of the Estuary with progressively lower salinities. The use of different species will affect direct comparability of data, at least for some contaminants. Contaminant concentrations in transplanted organisms also represent a kinetic view of contamination. In the RMP they reflect uptake after 90–100 days, which may or may not reflect steady state with concentrations in the environment. Finally, the spatial and temporal intensity of sampling transplanted organisms may be limited by the expense and cumbersome nature of the methods, transplanted individuals may not survive, or some locations may be unsuitable in terms of access, proper habitat, or interference from shipping or vandalism.

The most important concerns about the use of resident species as bioindicators include the availability of animals in critical locations or at critical times and the variability (or effects on interpretation) caused by differences in life cycle, size, or genetic and physiological changes. Resident bioindicator species can be absent from a location because the distribution is patchy or because of natural or anthropogenic stresses. The history of contaminant exposure is not known for resident species unless samples are collected intensively over time. Differences in contaminant history might affect interpretation of recent contamination or add variability to the responses of residents.

The use of resident species also has advantages. The organisms are living in the habitat of interest, and effects of caging or moving the animals is not a consideration in interpretations. Concentrations in tissues should also reflect natural steady state concentrations; or in highly variable environments temporal

variability and the history of changes in concentrations can be assessed directly by frequent sampling. While resident species may indeed be absent or difficult to collect in some circumstances, in other circumstances they may be more practical to collect frequently than would transplants or they may be present in areas otherwise unsuitable for deploying transplanted animals.

Uncertainties in employing resident bioindicators can be reduced by careful determination of the responsiveness of the species as well as the environmental accuracy and precision of responses to contamination (Brown and Luoma, 1995). Brown and Luoma (1995) studied use of the bivalve *Potamocorbula amurensis* as a resident bioindicator of metal exposures in North San Francisco Bay. They studied responses to metal exposures in this species in laboratory studies and in near monthly collections from six sites between January 1991 and March 1992. The most important advantage of employing this opportunistic species was its very broad distribution in the North Bay, where it has been abundant since 1987. *P. amurensis* is highly euryhaline (i.e., it tolerates wide salinity ranges and fluctuations) and available from a wide range of conditions in the North Bay. Breeding populations were found throughout the study period at a site toward the mouth of the Sacramento River (see Figure 1 in Chapter One: Introduction), where salinities ranged from 0.5 ‰ to 12.0 ‰. They were also found throughout most of Suisun and San Pablo Bays and in the South Bay, where salinities ranged from 25.2 ‰ to 31.8 ‰. Populations were found in a variety of types of sediment and intertidally as well as subtidally. Because *P. amurensis* was present throughout a contamination gradient in Suisun Bay, it was inferred that the species was at least moderately pollution-tolerant. Variability in metal concentrations was reduced to manageable levels with careful methodologies. To determine the effect of animal size, the shell length versus concentration regression was assessed for each metal at each site. Where correlation occurred, methods were presented

to counter such biases. Undigested gut content material did not cause a detectable bias in tissue concentrations where concentrations in particulate materials were substantially lower than concentrations in tissues (see *Quantification of Trace Element Measurement Errors in Bioaccumulation Studies Associated with Sediment in the Digestive Tract*, this report). For trace elements that occur in high concentrations in particles, a 24 hour depuration removed sufficient gut content to eliminate effects on tissue concentrations. Brown and Luoma (1995) also addressed the question of local variability in bioaccumulated metal that might result from the combination of biological and geochemical uncertainties (i.e., within a site, between adjacent sites, between adjacent times). The variability of replicates collected at one time and one place was similar to the variability among adjacent locations or times, if inputs did not change. Methodologies that employed relatively large numbers of organisms per sample (see Methods) had the statistical power to detect 20% differences in mean concentrations along regional gradients, at the higher range of the standard deviation (25%), and the sensitivity to detect 10% differences at the lower range of a typical standard deviation (12%). Although less detailed, earlier studies also showed the usefulness of employing the clams *Macoma balthica* (Luoma *et al.*, 1985) and *Corbicula* sp. (Luoma *et al.*, 1990) as resident bioindicators in North and South San Francisco Bay. However, neither of these species were distributed as widely in the Bay as *P. amurensis*.

The comparability of results between resident and transplant approaches has not been fully studied. In some circumstances transplanted organisms rapidly reach the same contaminant concentrations as native species (Bryan and Gibbs, 1983; Nelson *et al.*, 1995). However in other circumstances (especially contaminated environments), large differences between transplanted and resident species remained after months of exposure (Bryan and Hummerstone, 1978; Cain and Luoma, 1985; Widdows *et al.*, 1984).

## Selenium Trends in the North Bay

Bioindicators are especially effective in monitoring selenium (Se) contamination, one of the most important contaminants in the North Bay. The bivalves *Corbicula* sp., *Macoma balthica* and *Mytilus edulis* were all responsive to changes in Se exposure in San Francisco Bay in past studies, either as resident or transplanted species (Risebrough, 1977; Johns *et al.*, 1988). A distinct gradient in Se contamination, with maximum concentrations near Carquinez Straits, was a feature of North Bay in 1976 in *Mytilus edulis* (Risebrough, 1977) and 1985–1986 in *Corbicula fluminea* (Johns *et al.*, 1988). Se concentrations in suspended particulate materials were also highest near Carquinez Straits after the flood of 1986 (Cutter, 1989) but were more widespread later in the year, when river inflows were reduced and residence times were longer in San Pablo Bay and Suisun Bay.

Bivalves were effective bioindicators of Se distributions because of the pathway of Se bioaccumulation in the North Bay (Luoma *et al.*, 1992). The most important species of dissolved Se in the North Bay was selenite, which, when taken up by phytoplankton, was biotransformed to organo-selenium. Organo-selenium was efficiently transferred to bivalves (clams) that ingested phytoplankton with suspended particulate material (Luoma *et al.*, 1992). Direct exposure to dissolved Se was an insignificant source of exposure for the clams. The clams were a logical vector for Se exposure for diving ducks that contained high concentrations of Se (White and Hofman, 1988; Chadwick *et al.*, 1991). Selenium bioaccumulation in *P. amurensis* was not studied previously, even though it is now the predominant resident bivalve in the North Bay.

### Study Design

The goal of the present study was to compare selenium and mercury (Hg) concentrations in resident bivalves (principally *P. amurensis*) in the North Bay with concentrations determined in transplanted bivalves in the 1995 RMP studies. These elements were chosen

because they are two of the pollutants of greatest concern in San Francisco Bay. The data reported here are from May 1995 through June 1996. A period of drought in the watershed of San Francisco Bay ended in 1993 and especially in 1995; the latter was a year of exceptionally high and long-lasting riverine inflows into the system due to high precipitation and snowpack in the watershed (Cloern, this report). Hydrologic inputs to San Francisco Bay in 1996 were similar to the long-term average for the ecosystem. In contrast to the two relatively stable hydrologic years for metal bioaccumulation reported for *P. amurensis* by Brown and Luoma (1995), the temporal environmental influences that might affect the responses of a biosentinel species to contamination in the Estuary were probably accentuated in 1995 and 1996.

The comparison of transplanted and native species had four parts. The first goal was to compare bioaccumulated Se concentrations in different species. Assuming such concentrations might differ among species, the sampling was also designed to compare spatial trends in Se bioaccumulation indicated by the resident and transplanted bivalves. Resident clams were collected from three locations near RMP bagged bivalve sites in May 1996: Grizzly Bay (BF20), Davis Point at the mouth of Carquinez Strait (BD40), and San Pablo Bay near Pinole Point (BD30) (see Figure 1 in Chapter One: Introduction). Resident animals were also collected at USGS Station 8.1 in the Carquinez Strait, across the channel from the Napa River bagged bivalve site (BD50). *P. amurensis* were present at three of the four sites (they were absent at Davis Point). *Macoma balthica* were collected at Davis Point and, for comparison with *P. amurensis* at a site on the west side of Pinole Point. In the RMP, *Corbicula fluminea* was deployed in Grizzly Bay, and *Crassostrea gigas* at the other stations.

The third goal was to compare temporal variability in concentrations. In October 1995, *P. amurensis* were collected from five locations in the Napa River (including near bagged bivalve site BD50); and from United States

**Table 1. Determination of selenium and mercury in standard reference materials at the time of analyses of tissue samples by USGS Se-Hg laboratory.** \* July 19, 1995 run; \*\*August 1996 run. Reference materials were chosen to represent both sediments and tissues and to cover a range of Se and Hg concentrations. Laboratory results also were comparable with other laboratories in intercalibration exercises with NOAA-NRC Canada DORM reference materials.

| Reference | Sample          | Observed Se (mg/g)      | Certified Se (mg/g) | Observed Hg (mg/g)    | Certified Hg (mg/g) |
|-----------|-----------------|-------------------------|---------------------|-----------------------|---------------------|
| NIST      | SJS-sed         | 1.6, 1.6*               | 1.6 ± 0.1           | 1.3, 1.4*             | 1.4 ± 0.08          |
| NRC-Can   | DORM-1-sediment | 1.6, 1.9*<br>1.8, 1.8** | 1.6 ± 0.1           | 0.76, 0.81*<br>0.78** | 0.8 ± 0.07          |
| NIST      | Oyster          | 1.9, 1.9*               | 2.2 ± 0.2           | 0.08*                 | 0.06 ± 0.01         |
| IAEA      | MA-B-3 - Fish   | 1.2*<br>1.4, 1.5**      | 1.4–1.7             | 0.45, 0.50**          | 0.47–0.61           |
| NRC-Can.  | TORT-1          | 6.5*                    | 6.9 ± 0.5           | 0.30*, 0.29**         | 0.33 ± 0.06         |
| NRC-Can.  | TORT-2          | 5.5, 5.7**              | 5.6 ± 0.7           | 0.27, 0.25**          | 0.27 ± 0.06         |
| NRC-Can.  | DOLT-2          | 5.6, 6.2**              | 6.1 ± 0.5           | 2.11, 2.12**          | 1.99 ± 0.10         |

Geological Survey (USGS) sites in Suisun Bay (6.1), Carquinez Strait (repeat sampling at 8.1) and San Pablo Bay (subtidal site 12.5, comparable to BD30). Thus the May and October sampling of residents was comparable to the wet season, dry season sampling of the RMP.

The fourth goal was to repeatedly sample resident bivalves at one station to verify any temporal trends. *P. amurensis* were collected for Se analysis monthly, between December 1995 and June 1996 from Carquinez Strait (USGS 8.1). USGS 12.5 in San Pablo Bay was re-sampled in June 1996.

### Methods

Resident clams (*P. amurensis* or *Corbicula* sp.) were collected from the subtidal zone with a Van Veen grab and 1 or 2 mm sieves. Channel depths ranged from 8–20 m. The subtidal sites adjacent to marshes in Honker Bay and the Napa River (Figure 1 in Chapter One: Introduction) were located in the shallows at an average depth of 1–3 m. Clams (*P. amurensis* and *Macoma balthica*) were also collected intertidally at three sites, at low tide with a shovel, sieve and bucket. Between 60–120 clams of all sizes were collected at each time and each site and placed into containers of water collected at the site. The clams were kept in this ambient water in a constant temperature room at 10°C to depurate for 48 hours, as previous studies

showed a residence time of material in the gut of *P. amurensis* approximately 24 hours in this species (Decho and Luoma, 1991). Clams from each site were separated into size classes of 1 mm difference and composite samples were made of similar sized individuals. Samples of larger numbers of individuals were necessary for smaller size classes in order to obtain enough mass for analysis. Mean concentrations characteristic of a site and at a particular time were thus determined from analyses of usually 3 replicate composite samples each containing 20–60 clams (each composite was contained at least 250 mg dry weight soft tissue). Mercury and selenium were determined by Hydride Atomic Absorption Spectrophotometry. A separate subsample was decomposed for mercury as well as one for selenium. Mercury subsamples were digested at 100°C in *aqua regia*, re-digested in 10 percent nitric acid plus potassium dichromate and then reduced at the time of the hydride analysis. Selenium subsamples were digested in concentrated nitric and perchloric acids at 200°C and reconstituted in hydrochloric acid.

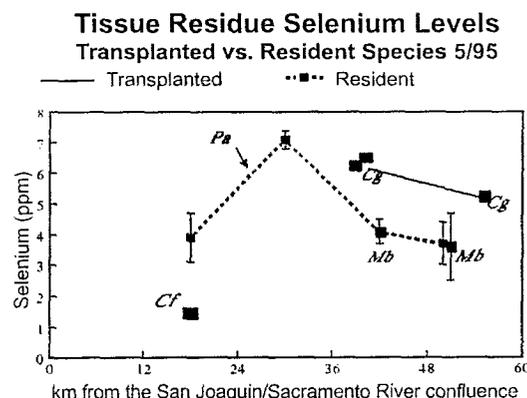
All glassware and field collection apparatus were acid-washed, thoroughly rinsed in ultra-clean deionized water, dried in a dust-free positive-pressure environment, sealed and stored in a dust free cabinet. Quality control was maintained by frequent analysis of blanks.

analysis of National Institute of Standards and Technology standard reference materials (tissues and sediments) with each analytical run, and internal comparisons with prepared quality control standards. A full QA/QC plan is available upon request. Analyses of National Institute of Technical Standards (NITS) reference materials (oyster tissue, San Joaquin soils) were within an acceptable range of certified values reported by NITS or were consistent where the nitric acid digest did not completely decompose the sediment samples (see Brown and Luoma, 1995 and Luoma *et al.*, 1995 for metals; see Table 1 for Hg and Se).

**Spatial Trends: May 1995**

Concentrations of Se observed in resident and bagged bivalves are compared in Table 2 and Figure 19. Bioaccumulation of Se differed among some, but not all species, when compared at the same location. *P. amurensis* appeared to accumulate Se more efficiently than *C. fluminea*. In Grizzly Bay, concentrations of Se in *C. fluminea* were 1.35 mg/g compared to  $3.90 \pm 0.8$  mg/g in *P. amurensis*. At comparable locations, concentrations in *C. gigas* were slightly greater than concentrations in *P. amurensis* (5.43 mg/g compared to  $3.70 \pm 0.7$  mg/g, respectively, in San Pablo Bay) and *M. balthica* (6.52 mg/g compared to  $3.60 \pm 1.1$  mg/g at Davis Point) in May. *M. balthica* and *P. amurensis* did not differ significantly in Se concentrations at Pinole Point ( $p > 0.1$ ).

Spatial distributions observed in the resident species were generally similar to those indicated by the transplanted bivalves in May 1995, although some details differed. If all bivalve data were compared, the RMP data indicated that Se concentrations were lower in Grizzly Bay in May 1995 than in San Pablo Bay, the Napa River, and at Davis Point. This was due to the difference in bioaccumulation between *C. fluminea* and *C. gigas*. Bioaccumulated Se concentrations were similar in Grizzly Bay and San Pablo Bay in *P. amurensis*. If it is assumed that concentrations



**Figure 19. Spatial trends in concentrations of Se in soft tissues of transplanted *Crassostrea gigas* (Cg) and *Corbicula fluminea* (Cf) compared to trends in concentrations in resident *Potamocorbula amurensis* (Pa) and *Macoma balthica* (Mb) in May 1995, as a function of distance from the San Joaquin/Sacramento River confluence.**

**Table 2. Comparison of selenium concentrations in transplant and resident species in the North Bay in May 1995.** Locations are km from the mouth of the San Joaquin/Sacramento Rivers confluence.

| Site                      | Location | Species:<br>Transplant | Se<br>(mg/g dry) | Species:<br>Resident | Se<br>(mg/g dry) | Location |
|---------------------------|----------|------------------------|------------------|----------------------|------------------|----------|
| Grizzly Bay               | 18 km    | <i>C. fluminea</i>     | 1.35             | <i>P. amurensis</i>  | 3.90<br>(0.8)    | 18 km    |
| Napa River<br>(Carquinez) | 39 km    | <i>C. gigas</i>        | 6.22             | <i>P. amurensis</i>  | 7.10<br>(0.3)    | 30 km    |
| Davis Point               | 40 km    | <i>C. gigas</i>        | 6.52             | <i>M. balthica</i>   | 4.10<br>(0.4)    | 42 km    |
| San Pablo Bay             | 55 km    | <i>C. gigas</i>        | 5.43             | <i>P. amurensis</i>  | 3.70<br>(0.7)    | 50 km    |
| San Pablo Bay             |          |                        |                  | <i>M. balthica</i>   | 3.60<br>(1.1)    | 50 km    |

in *M. balthica* are comparable to *P. amurensis*, Grizzly Bay was similar to Davis Point.

Probably the most important difference between the resident species survey and the RMP bagged bivalves was the elevated concentrations of Se observed in Carquinez Straits in *P. amurensis*. This aspect of Se distributions was slightly ambiguous in the RMP, because bivalves were not deployed in this waterway. This was an instance where the widespread nature of the resident species and relative ease of collection offered an advantage compared to the transplant approach. Because Se enrichment in Carquinez Strait was also indicated in earlier studies; this location might be considered a critical site for biomonitoring in the future.

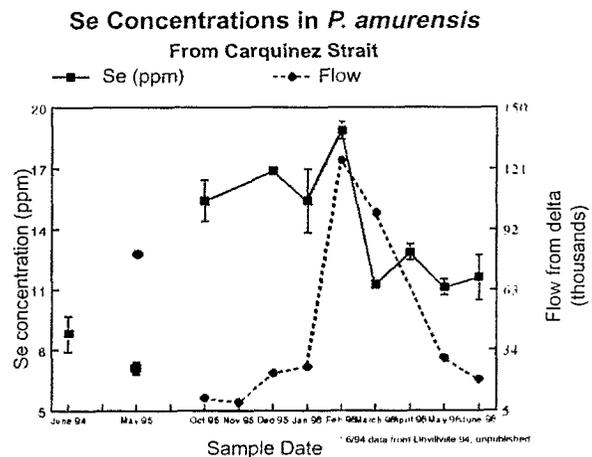
The spatial distribution and concentrations of Se observed in transplanted and resident species in May, 1995, may have been influenced by the hydrologic regime at the time. The RMP deployment and the May resident samplings occurred in the middle of a prolonged period of high river inflow. During low flow periods (summer and fall) the total outflow index at Chippis Island, calculated by the US Bureau of Reclamation, is typically less than 7,000 cubic feet per second (cfs). In the 1995 water year (October 1994 to October 1995) outflow first exceeded 10,000 cfs during 15 days in December 1994. Between January and the end of June average daily outflow for each month was 44,000–80,000 cfs (United States Bureau of Reclamation Delta Outflow Computation Tables, unpublished); outflows greater than 10,000 cfs continued into September.

### Temporal Trends

Significant differences in Se trends were observed between resident *P. amurensis* and bagged bivalves in October 1995. Concentrations in *P. amurensis* indicated a substantial increase in Se contamination in Suisun Bay, San Pablo Bay, and the Napa River in the resident food web by October 1995. An unambiguous increase was not indicated in the deployed bivalves.

In the RMP, Se concentrations in *C. fluminea* transplanted to Grizzly Bay were 1.35 mg/g deployment (Figure 8). The latter are not exceptionally high concentrations for *C. fluminea*; they are below the higher values observed by Johns *et al.* (1988) near Grizzly Bay in this species in 1985–1986. Concentrations of Se in *C. gigas* transplanted to the Napa River were only slightly higher (statistical significance could not be determined) in October compared to May. Concentrations of Se were substantially lower in October than May in *C. gigas* transplanted to Davis Point. Concentrations of Se in mussels at Pinole Point were not high in October, compared to those observed by Risebrough *et al.* (1977); and Se was not determined in bagged bivalves from San Pablo Bay in October. Thus, the RMP data alone did not indicate any great change in the relatively low levels of Se in the food web of the Suisun/San Pablo Bay region between May and October 1995.

In contrast to the RMP results, substantial, statistically significant increases in Se concen-



**Figure 20. Concentrations of Se in soft tissues of resident *Potamocorbula amurensis* collected subtidally from Carquinez Straits (USGS 8.1) and average monthly river inflow in thousands of cubic feet per second, as computed by the US Bureau of Reclamation for the time period May 1995 through June 1996. Data from June 1994 are also shown as reported by Linville, R. and Kegley, S. E. Selenium enrichment surrounding oil refineries: Analysis of *Potamocorbula amurensis* and sediment. 1994 Biology Fellows Undergraduate Research Symposium, Berkeley, CA.**

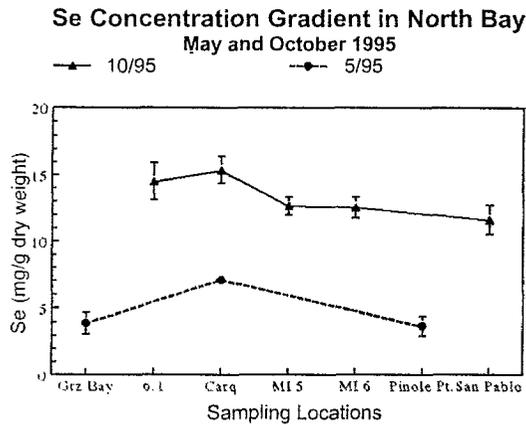


Figure 21. Spatial trends of Se concentrations in tissues of *Potamocorbula amurensis* in May 1995 and October 1995.

trations in *P. amurensis* were observed between May and October 1995. Concentrations at all locations in October were the highest ever reported for bivalves in North Bay, ranging from a maximum of  $15.4 \pm 1.0$  mg/g at USGS 8.1 in Carquinez Strait to a minimum of  $11.6 \pm 1.1$  mg/g at USGS 12.5 in San Pablo Bay (Figures 20 and 21; Table 3). Concentrations were also elevated throughout the Napa River (ranging from  $12.5 \pm 1.0$  mg/g to  $15.3 \pm 1.0$  mg/g at the six sites) in October. All concentrations in *P. amurensis* were substantially higher than observed in *C. gigas* at comparable locations, in contrast to the May results. All values exceeded the concentrations of Se that cause adverse effects in fish and birds when ingested in food (i.e. >10 mg/g).

Highly elevated Se concentrations were observed repeatedly in Carquinez Strait between October 1995 and June 1996. Concentrations of Se in *P. amurensis* ranging from  $15.4 \pm 1.0$  mg/g to  $18.9 \pm 0.4$  mg/g were observed between October 1995 through February 1996 at station 8.1. Concentrations declined slightly, to a range of  $10.0 \pm 0.7$  µg/g to  $12.8 \pm 0.4$  µg/g, between March 1996 and June 1996. The decline in concentrations coincided with the annual increase mean monthly river inflow to North Bay (Figure 20).

Figure 22 summarizes results from past studies with bivalves in the North Bay, showing mean concentrations of Se for each species

studied at the station nearest Carquinez Strait. Elevated Se concentrations have been observed in all studies since 1976. However, mean concentrations in the dominant bivalve in the system (*C. fluminea* in 1985 compared to *P. amurensis* in 1996) have almost tripled in recent years, suggesting the possibility of a large increase in Se dose to upper trophic level organisms feeding on bivalves. Oysters transplanted in a study in 1985 achieved a concentration very similar to oysters transplanted in 1996. On the other hand, the ambiguities of the oyster results between May and October in the RMP raise questions about whether bagged oysters would be sensitive to increases in environmental concentrations. It cannot be discounted that Se concentrations in Carquinez Strait increased after October 1995. But it is also possible that the higher Se in 1995–1996 compared to 1985–1986 might be the result of the replacement of *C. fluminea* by the invasion of a species that bioaccumulates Se more efficiently, the opportunist *P. amurensis*. Dissolved Se concentrations were not determined in October, and in 1995 elevated river

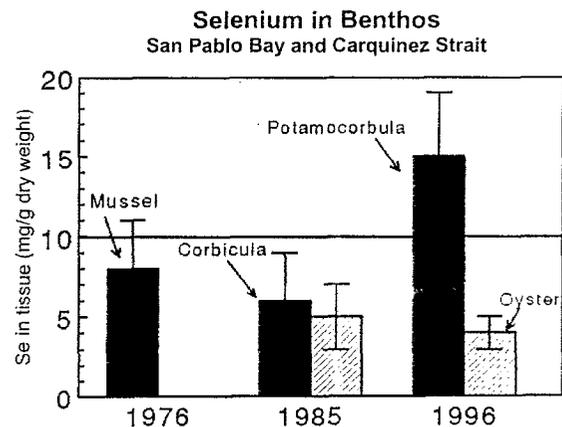


Figure 22. Selenium concentrations in tissues of mussels (transplanted *Mytilus californianus*, as reported by Risebrough, 1977), *Corbicula fluminea* (resident species, as reported by Johns *et al.*, 1988), transplanted oysters (*Crassostrea gigas*) and *Potamocorbula amurensis*. All values are grand means of all analyses conducted at the station nearest Carquinez Strait in each study.



inflows were present when the August sampling of Se was conducted.

Accumulation factors in *C. gigas* exceeded 1 in the wet season in the RMP transplant. This indicates that Se was taken up when animals were deployed from uncontaminated environments to the North Bay. However, accumulation factors in the dry season (October) in both *C. gigas* and *M. edulis* were low, indicating little Se uptake after deployment. It is possible that deployed animals either were feeding little during the dry season, or were feeding on a food source of lower Se bioavailability than that experienced by the resident species. The reduced condition indices of both *C. gigas* and *M. californianus* in October support the former contention (Figure 18). Detrital freshwater algae could be an important food source for filter feeders in North Bay, especially during periods of high river inflows. Such sources are less available during low flow periods. Behavioral changes as a result of the deployment or as a result of high Se concentrations on particulate materials are possible. But it seems more likely that the low standing stock of phytoplankton and algal detritus in North Bay affected the feeding or availability of food to *C. gigas* and *M. californianus* in October. If so, differences in food sources between deployed and resident species must be a consideration in interpreting transplant data, especially with regard to elements like Se that are bioaccumulated from food. One possible explanation may be the change in phytoplankton standing stock in the water column of the North Bay in recent years. Transplanted mussels or oysters may not be feeding the way they have in the past, affecting their exposures to Se.

### Summary of Selenium Comparison

The differences between trends in resident species and those in transplanted bivalves were small in May 1995. The most important difference may have been the lack of an RMP station in the region most influenced by Se inputs: Carquinez Strait. However, it is of concern that the substantial change in the Se contamination

of the benthos in the North Bay that occurred in October 1995, was not indicated by data from deployed bivalves, especially *C. gigas* and *M. edulis*. It becomes important to better understand the food source(s) exploited during periods of low river inflows by the highly successful *P. amurensis*, because that appears to carry Se in a form that is highly bioavailable during a time when vulnerable migratory species (e.g., diving ducks) are arriving in San Francisco Bay. Alternatively, deployed bivalves may obtain food in a manner different from how resident animals obtain food.

The temporal trends in Se concentrations in *P. amurensis* in the North Bay point out the interactions among the important issues affecting San Francisco Bay. River inflow appeared to influence bioavailable Se concentrations in North Bay in 1995 and 1996, presumably by affecting residence times and dilution of local Se inputs by freshwater. Concentrations of Se were lowest in *P. amurensis* during a prolonged period of high inflows (May 1995) and increased greatly after inflows subsided in October 1995. Similarly, the concentrations of Se in the transplanted *C. fluminea* were lower than any concentrations observed in resident *C. fluminea* by Johns *et al.* (1988) during 1985–1986. The latter study included no period of high river flow as prolonged as occurred in May 1995. A smaller decrease in Se bioaccumulation also occurred coincident with the pulse of high inflows in January–March 1996. Further investigation is warranted of the potentially important linkage between these issues.

The susceptibility of the Bay to invasions by exotic species also appeared to affect Se contamination of the food web. After the invasion of the Estuary by *P. amurensis* in 1986, Se concentrations in dominant resident bivalve in 1996 increased to levels three times greater than the contamination of the dominant bivalves in the mid-1980. Whatever the cause, it is clear that predators of bivalves in the food web of the North Bay could have been exposed to much more Se in 1996 than they were in the late 1980, when most studies of upper trophic levels were conducted.

## Mercury Concentrations in Bagged and Resident Bivalves

Mercury concentrations were low in *P. amurensis* (0.08–0.24 mg/g) at all locations studied in the North Bay and at all times (Table 4). No spatial trends were evident in the data. Concentrations doubled between May 1995 and October 1995 to June 1996; but the increase in absolute terms was small. Mercury concentrations in the two resident bivalves included in this study were not comparable. Concentrations in *M. balthica* were higher than concentrations in *P. amurensis* at Pinole Point. Comparing mercury concentrations in *M. balthica* between Pinole Point and Davis Point suggested greater contamination in resident species at the former site in May 1995.

Mercury concentrations in bagged bivalves ranged from 0.14–0.39 mg/g in May and October 1995 at the North Bay sites, approximately the same range as the resident species. The bagged bivalve data indicated that greater contamination occurred during the dry season than during the wet season, as observed in *P. amurensis*. The highest mercury concentrations in the RMP data and in the resident species data was observed at Pinole Point (~ 3.9 mg/g in *M. californianus* in October 1995; Figure 6), although it was unclear if the different species were directly comparable.

Bagged bivalves and resident species thus showed generally the same trends in mercury contamination in the North Bay. Most important, both indicated that substantial mercury contamination was not found in the benthos of the North Bay, either during high flows or during wet flows. Johns *et al.* (1988) drew similar conclusions from mercury analyses of *C. fluminea* at six sites in the North Bay in September 1986. They observed a range of concentration of 0.08–0.18 mg/g Hg dry weight among sites, similar to the concentration observed in bagged *C. fluminea* in May, 1995, but less than the 0.30 mg/g observed in RMP collections in October 1995.

Mercury contamination has been found in longer-lived higher trophic level species in the North Bay. That contamination may not be transferred via the benthic food web. Interactions between mercury and selenium have also been reported in the literature. If such interactions occur in North San Francisco Bay, they have only a minor influence on concentrations. Mussels and *M. balthica* may be the best bioindicators for mercury contamination in the benthos of San Francisco Bay.

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**Table 4. Mercury concentrations in mg/g dry weight in *Potamocorbula amurensis* and *Macoma balthica* at five locations in North San Francisco Bay (Figure 1 in Chapter One: Introduction) in October, 1995; between October 1995 and June 1996 at Station 8.1 in Carquinez Strait and at station 12.5 in San Pablo Bay in June 1996. Mercury concentrations in *Macoma balthica* also shown for May 1995. Values are means ± one standard deviation. (#) is the number of composites analyzed. Each composite included approximately 50 individual *P. amurensis*, and >250 mg dry weight soft tissue. Napa River stations are numbered North-to-South ascending.**

| Site                 | 5/95          | 10/95        | 12/95   | 1/96         | 2/96         | 6/96         |
|----------------------|---------------|--------------|---------|--------------|--------------|--------------|
| <i>P. amurensis.</i> |               |              |         |              |              |              |
| Carquinez Straits    | 0.10±0.00 (2) | 0.18±.01 (3) | 0.2 (1) | 0.21±.02 (3) | 0.24±.01 (3) | 0.19±.02 (3) |
| San Pablo Bay        | 0.08±.01 (3)  |              |         |              |              |              |
| Napa 1               |               | 0.21±.01 (3) |         |              |              |              |
| Napa 3               |               | 0.20±.02 (3) |         |              |              |              |
| Napa 5               |               | 0.23±.01 (2) |         |              |              |              |
| <i>Macoma</i>        |               |              |         |              |              |              |
| Davis Point          | 0.24±.04 (3)  |              |         |              |              |              |
| San Pablo Bay        | 0.37±.04 (4)  |              |         |              |              |              |