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Increased selenium threat as a result of invasion of the exotic bivalve *Potamocorbula amurensis* into the San Francisco Bay-Delta

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Abstract

Following the aggressive invasion of the bivalve, *Potamocorbula amurensis*, in the San Francisco Bay-Delta in 1986, selenium contamination in the benthic food web increased. Concentrations in this dominant (exotic) bivalve in North Bay were three times higher in 1995–1997 than in earlier studies, and 1990 concentrations in benthic predators (sturgeon and diving ducks) were also higher than in 1986. The contamination was widespread, varied seasonally and was greater in *P. amurensis* than in co-occurring and transplanted species. Selenium concentrations in the water column of the Bay were enriched relative to the Sacramento River but were not as high as observed in many contaminated aquatic environments. Total Se concentrations in the dissolved phase never exceeded 0.3 μg Se per l in 1995 and 1996; Se concentrations on particulate material ranged from 0.5 to 2.0 μg Se per g dry weight (dw) in the Bay. Nevertheless, concentrations in *P. amurensis* reached as high as 20 μg Se per g dw in October 1996. The enriched concentrations in bivalves (6–20 μg Se per g dw) were widespread throughout North San Francisco Bay in October 1995 and October 1996. Concentrations varied seasonally from 5 to 20 μg Se per g dw, and were highest during the periods of lowest river inflows and lowest after extended high river inflows. Transplanted bivalves (oysters, mussels or clams) were not effective indicators of either the degree of Se contamination in *P. amurensis* or the seasonal increases in contamination in the resident benthos. Se is a potent environmental toxin that threatens higher trophic level species because of its reproductive toxicity and efficient food web transfer. Bivalves concentrate selenium effectively because they bioaccumulate the element strongly and lose it slowly; and they are a direct link in the exposure of predaceous benthivore species. Biological invasions of estuaries are increasing worldwide. Changes in ecological structure and function are well known in response to invasions. This study shows that changes in processes such as cycling and effects of contaminants can accompany such invasions. © 2002 Published by Elsevier Science B.V.

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(Cutter, 1989). All values are plotted as a function of salinity. Arrows depict the location of Carquinez Strait in each transect. Selenium concentrations in the Bay in 1995–1996 exceeded those in the Sacramento River, as in previous studies (0.065 ± 0.022 μg Se per l; Cutter and San Diego-McGlone, 1990). The highest concentration in the Bay was 0.29 μg l^{-1}. Within the Bay-Delta the concentrations at most stations followed the order June 1995 < October 1996 < September 1986, but the differences among the three transects were small, and appear to fall with the range of variation defined by Cutter and San Diego-McGlone (1990). The shape of the October 1996 transect differed from that in September 1986 because of elevated selenium concentrations at the upstream-most station, perhaps indicating some San Joaquin input. Total dissolved Se concentrations were low compared with the USEPA water quality standard of 5 μg Se per l (Environmental Protection Agency, 1992).

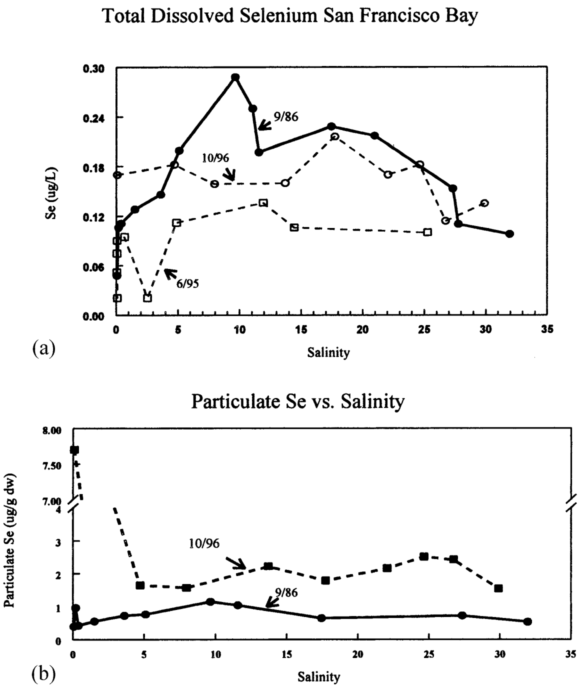

Fig. 3. (a) Dissolved Se concentrations (μg Se per l) as a function of salinity, determined in transects across the salinity gradient of North San Francisco Bay in September 1986 (Cutter, 1989), June 1995 and October 1996. (b) Concentrations of particulate Se (μg Se per g dw) as a function of salinity determined in transects across the salinity gradient of North San Francisco Bay in September 1986 (Cutter, 1989) and October 1996.

Particulate selenium is the variable most likely to ultimately determine selenium bioavailability (Luoma et al., 1992). Concentrations of selenium on suspended particulate material were determined only in October 1996, during the present study. Particulate selenium was uniformly higher in Oct 1996 than in the estuarine transect conducted in September 1986 (Cutter, 1989; Fig. 3(b)). The highest concentration was observed in the river station in October 1996 (nearly 8 μg g^{-1} dw), again indicating particulate selenium inputs from the San Joaquin River were possible (subsequent studies have not found these high values, however; Cutter et al., unpublished data).

4.3. Selenium in *P. amurensis*

4.3.1. Spatial variability

Among the stations that were sampled in May 1995, selenium concentrations in soft tissues of *P. amurensis* ranged from 3.7 ± 0.7 to 7.1 ± 0.3 μg Se per g dw (Table 1). Se concentrations were higher in *P. amurensis* from the Carquinez Strait (7.1 μg Se per g dw), than ($P < 0.01$) in the shallows of Suisun Bay (3.9 μg Se per g dw) and San Pablo Bay (3.7 μg Se per g dw). The latter two sites were not statistically different. Concentrations in October 1995 were higher than in May 1995. Se in *P. amurensis* from Carquinez Strait (15.4 μg Se per g dw) and Suisun Bay (14.5 μg Se per g dw) were not statistically different; but both were higher than Se concentrations in San Pablo Bay (11.6 μg Se per g dw; $P < 0.05$; Table 1). Concentrations were also elevated in the tidal Napa River compared with May concentrations in the North Bay.

Concentrations of Se in *P. amurensis* in October 1996 were similar to October 1995 (Table 1; Fig. 4). The range of mean Se concentrations in *P. amurensis* was 6.9–8.7 μg Se per g dw in San Pablo Bay, and 5.9–20 μg Se per g dw in Suisun Bay. The greatest enrichment was observed in the Carquinez Strait (20.0 μg Se per g dw). Higher concentrations were observed toward the rivers, at stations S1–S6, compared with other shallow water locations in Suisun Bay or San Pablo Bay

Table 1
Selenium concentrations in μg g^{-1} dw in *P. amurensis* at 29 locations in North San Francisco Bay (Fig. 1) in May 1995, October 1995, and October 1996

Site	Se (μg g^{-1} dry)	Standard deviation (S.D.)	Sample composites
May 1995			
Grizzly Bay	3.9	0.8	5
8.1 (Carq. Straits)	3.7	0.7	3
San Pablo Bay-Pinole Pt.	7.1	0.3	3
October 1995			
6.1	14.5	1.4	3
8.1 (Carq. Straits)	15.4	1.0	3
12.5 (San Pablo)	11.6	1.1	5
Napa 1	12.5	1.0	3
Napa 2	15.3	n/a	1
Napa 3	14.1	0.5	3
Napa 4	14.0	0.9	3
Napa 5	12.7	0.7	2
Napa 6	12.6	0.8	5
October 1996			
4.1	11.0	1.0	7
6.1	16.8	1.6	5
8.1 (Carq. Straits)	20.0	1.4	4
12.5 (San Pablo)	8.7	2.1	4
S1	9.6	0.2	2
S2	9.2	0.1	2
S3	7.5	0.1	2
S4	10.0	0.0	2
S5	8.9	0.4	5
S6	10.3	0.8	2
S7	5.9	1.6	4
S8	6.1	0.3	2
S9	8.2	0.7	4
S10	6.7	0.2	3
S11	7.3	0.3	4
S12	8.3	0.3	2
S13	8.1	0.5	2
S14	8.1	0.7	3
S15	6.9	1.2	3
S16	7.5	0.3	3
S17	7.9	0.7	2

Each sample composite included approximately 20–60 individual *P. amurensis*, and >250 mg dw soft tissue. Napa River stations are numbered North-to-South ascending. Stations S1–S17 are in shallow water.

($P < 0.001$; Table 1; Fig. 4). Like dissolved and particulate concentrations in October 1996, the higher concentrations toward the rivers in *P. amurensis* could have reflected inputs from the San Joaquin River.

Thus all three samplings of bivalves indicate that Se concentrations in *P. amurensis* are enriched compared with background concentrations typical of bivalves (<3 μg Se per g; Johns et al., 1988) and that enrichment is widespread through North San Francisco Bay. Concentrations varied nearly 4-fold among sites. The observation of the highest concentrations near Carquinez Strait is consistent with past studies (Cutter, 1989; Johns et al., 1988) and the previously identified refinery source of Se input. Dilution of contamination (i.e.

bioaccumulation in *P. amurensis* and the transplants, *C. fluminea*, *C. gigas* or *M. californianus*. Phytoplankton blooms in Suisun Bay have essentially disappeared since the *P. amurensis* invasion, presumably due to consumption of primary production by the invasive bivalve. It is notable that condition index appeared to decline in all transplants in both October experiments (Table 2). Reduced condition index after deployment suggests that the deployed bivalves were not feeding normally in the fall. Uptake from food is the predominant route of selenium exposure (Luoma et al., 1992; Wang and Fisher, 1999). Therefore, it is possible that non-feeding deployed animals were not exposed to environmental selenium. The deployed animals gave no indication that high selenium concentrations were common in the predominant benthic species in North Bay during the season of low river inflows. Thus, the transplanted animals did not provide an accurate picture of selenium contamination in the estuary, and did not reach the level of selenium contamination found in *P. amurensis*.

4.7. Consequences of high selenium concentrations in P. amurensis

Bivalves are a critical link for passing selenium to benthivores because trophic transfer is the primary route of predator exposure (Lemly, 1985). The highest concentrations of Se in *P. amurensis* are especially significant in that they exceed values that other studies have shown reduce growth or cause reproductive damage when ingested in experiments by birds and fish (Hamilton et al., 1990; Heinz et al., 1989). Teratogenicity, effects on hatchability of eggs and reduced growth of young life stages have a threshold of occurrence above 3–10 μg Se per g dw in food in various studies (Lemly, 1998; Hamilton, 1999; Heinz et al., 1989). A high frequency of adverse effects is found when concentrations in food (prey) exceed 10–11 μg Se per g dw (Skorupa, 1998; Adams et al., 1998). The highest concentrations in *P. amurensis* exceed the latter value by two-fold.

Some of the important resource species in the North Bay/Delta eat *P. amurensis* and presumably other bivalves (sturgeon, diving ducks such as scoter and scaup, dungeness crab; Carlton et al., 1990). Earlier studies (White et al., 1988; Urquhart and Regalado, 1991) showed that these benthivores were the predators with the highest selenium concentrations. Average yearly Se concentrations in the liver of the diving duck, surf scoter, ranged from 75 to 200 ug g^{-1} dw in 1986–1990, a 7- and 14-fold increase from a reference site (Humboldt Bay). White sturgeon captured between 1986 and 1990 contained annual average concentrations ranging from about 9–30 ug Se per g dw in liver ($n = 52$); and 7–15 ug Se per g dw in flesh ($n = 99$). In 1986, the Dungeness crab had an average soft tissue concentration of 15 ug Se per g dw, which was a three fold increase from the reference site (Humboldt Bay). Predators that fed from the water column (e.g. striped bass) seemed to have lower selenium concentrations than the benthivores.

If the susceptibility of San Francisco Bay to invasion by the exotic species *P. amurensis* (Carlton et al., 1990) caused greater Se contamination in the benthos, this effect could be passed on to benthivores. Little data is available to evaluate selenium concentrations in benthivores after 1990. But the 5-year Se Verification Study extended from 1986 through 1990 (Urquhart and Regalado, 1991). *P. amurensis* was first observed in the Bay in 1986 and became well established by 1988 (Carlton et al., 1990; Nichols et al., 1990). Annual mean selenium concentrations in bivalves and two benthivores, sturgeon and scoter, were collected simultaneously in that study and in several of the years between 1986 and 1990. Bivalve selenium concentrations (not including *P. amurensis*) and benthivore concentrations were strongly correlated in that data set (Figs. 6 and 7). The highest values in benthivores were observed in 1989 and 1990. If the mean concentration of selenium in *P. amurensis* was inserted into Fig. 7 at the 1989–1990 benthivore concentration, the added point is consistent with changing selenium exposures of predators. Thus preliminary analysis indicates that the successful invasion of this new resident of Suisun Bay could have changed the exposure of at least some predators in this system.

5. Conclusions

Invasion of San Francisco Bay by the exotic bivalve, *P. amurensis*, resulted in an increase by threefold of selenium concentrations in the predominant macrobenthic food in the estuary. Se concentrations in bivalve-consuming benthivores in the North Bay appeared to increase between the time *P. amurensis* populations were first observed (1986, Carlton et al., 1990) and when it became established as the predominant benthic species (~ 1988–1990; Urquhart and Regalado, 1991). This is of concern because Se is a strong reproductive toxin for such species, and Se concentrations in *P. amurensis* in fall 1995 and 1996 were in excess of the toxicologic threshold for adverse effects on such predators. Se-contaminated *P. amurensis* were widespread in Suisun and San Pablo Bays in 1995 and 1996. Seasonal variability is an important feature of selenium contamination in *P. amurensis*, with the highest concentrations occurring in fall during the period of longest hydraulic residence times. Transplanted bivalves were not good surrogate indicators for exposure and contamination of the resident bivalve.

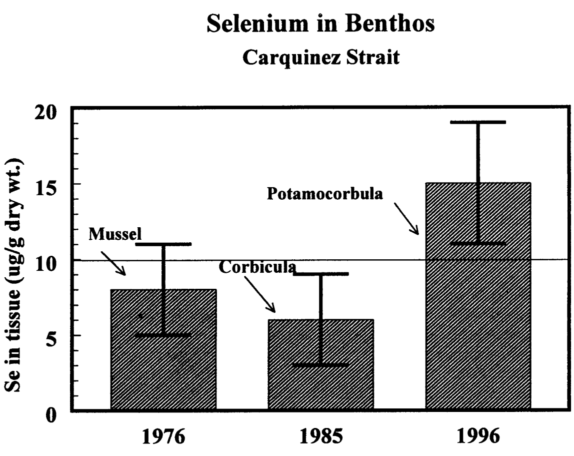

Fig. 6. Mean and S.D. of Se concentrations (μg Se per g dw) in three studies of bivalves from in or near Carquinez Strait in three different decades. ‘Mussels’ were studies of transplanted *M. edulis* in 1976 (Risebrough et al., 1977); ‘Corbicula’ represents mean of 67 samplings of the clam *C. fluminea* (Johns et al., 1988) and ‘Potamocorbula’ is the mean of all Carquinez samples in the present study.

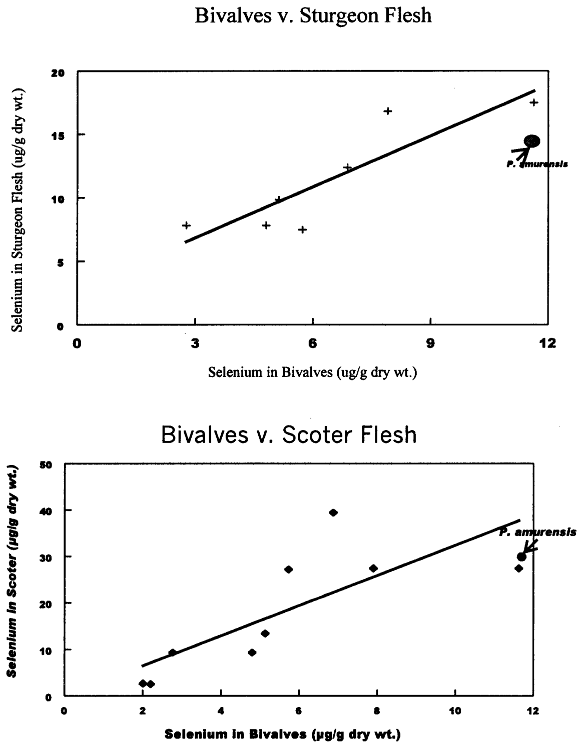

Fig. 7. Relationships between Se concentrations in resident bivalves (data from White et al., 1988; Urquhart and Regalado, 1991; Johns et al., 1988) and either sturgeon flesh or the flesh of the diving ducks (surf scoter) from North San Francisco Bay and Humboldt Bay (data from White et al., 1987, 1988, 1989; Urquhart and Regalado, 1991). Predators and prey were sampled in the same season, year and sub-bay. Mean Se concentration in *P. amurensis* at Carquinez in 1995 is superimposed on each graph to match predator data from 1989–1990, because *P. amurensis* was probably the primary food of these predators in 1989–1990.

We did not fully disprove the hypothesis that the invasive species, *P. amurensis*, is not more efficient at bioaccumulating selenium than other bivalves, although some evidence points in that direction. But this is not the only way an invasive species can affect the fate and effects of a contaminant. The efficient bioaccumulation of Se by bivalves, in general, and the efficient dietary transfer of Se from bivalves to higher trophic levels means that an invasion that shifts the structure of an estuarine community toward dominance by a bivalve-based benthic food web can enhance adverse effects of selenium in the system, by expanding the availability of a contaminated food supply. Whatever the basic mechanism, it seems clear that the invasion of the non-native bivalve *P. amurensis* has resulted in increased bioavailability of a potent environmental toxin to certain benthivores in San Francisco Bay. Changes in contaminant cycling and potential effects are yet another reason to be concerned by the threat of invasive species in our estuarine ecosystems (Cohen and Carlton, 1998; Carlton and Geller, 1993).

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