CHAPTER 5

Bivalve Monitoring

Bivalve Monitoring

Background

The purpose of monitoring contaminant concentrations in bivalve tissue for the RMP is two-fold. First, bivalves integrate the bioavailable portion of contaminants in the water column over time, and second, for many contaminants, bivalves are good indicators of contaminant transfer from water into the food web. Bivalves will accumulate certain contaminants in concentrations much greater than those found in ambient water (Vinogradov, 1959). This phenomenon is a result of the limited ability of bivalves to regulate the concentrations of most contaminants in their tissues. This method of active biomonitoring has been widely applied by the California State Mussel Watch Program (Phillips, 1988; Rasmussen, 1994) and others (Young *et al*., 1976; Wu and Levings, 1980; Hummel *et al*., 1990; Martincic *et al*., 1992). For reviews of bioaccumulation monitoring, see Luoma and Linville (1996) and Gunther and Davis (1997).

Bivalves were collected from sites thought to be uncontaminated and transplanted to 15 stations in the Estuary during the wet season (May) and the dry season (September; see map on the inside of the front cover). Sampling dates are listed in Table 1.2 in *Chapter 1: Introduction*. Contaminant concentrations in tissues, survival, and biological condition were measured before deployment (referred to as time zero (T-0) or background) and at the end of the 90–100 day deployment period. Because of the variability between each individual bivalve organism, composite samples of tissue were made from T-0 organisms and from surviving organisms from each deployment site (up to 45 individuals) for analyses of trace contaminants. The *Corbicula* reference site was not optimal, since initial concentrations were found to be high after changing the site from Lake Isabella to Putah Creek and a pond at UC Davis.

The effects of high short-term flows of freshwater on the transplanted bivalves west of Carquinez Strait were minimized by deploying the bivalves near the bottom where density gradients tend to maintain higher salinities. All bivalves were kept on ice after collection and deployed within 72 hours. Multiple species were deployed at several stations due to uncertain salinity regimes and tolerances. Detailed sampling and analysis methods are included in *Appendix A*. Data are tabulated in *Appendix C*.

Overall, the bivalve bioaccumulation and condition study objectives for 1997 were met, although the unusual wet season with extremely high freshwater inputs in January caused high mortality rates in *Mytilus* spp. during the winter/spring deployment.

Accumulation Factors

In addition to using the absolute tissue concentrations at the end of each deployment period and comparing them to initial tissue concentrations prior to transplanting the bivalves to the Estuary (T-0), this report uses accumulation factors (AFs) to indicate accumulation or depuration (loss of constituents from bivalve tissue) during the 90–100 day deployment period. The accumulation factor is calculated by dividing the contaminant concentration in transplants by the initial bivalve concentration at T-0. For example, an accumulation factor of 1.0 indicates that the concentration of a specific contaminant remained the same during the deployment period compared to the initial contaminant level prior to transplanting the bivalve sample to the Estuary. An AF less than 1 indicates that the bivalves decreased in contaminant concentration during the deployment period, while an AF above 1 indicates accumulation.

Guidelines

In the following figures (Figures 5.1–5.16), tissue concentrations of various trace contaminants are compared to applicable guidelines in the proposed California Toxics Rule, since these threshold levels represent the most recent and most scientifically defensible values available to date.

Tissue guidelines are expressed in ppm wet weight, while the RMP tissue data are presented as ppm dry weight. A wet-to-dry weight conversion factor of 7, based on an average of 85% moisture content in bivalves, was applied for comparisons.

Biological Condition and Survival

The biological condition (expressed as the ratio of dry tissue weight to shell cavity volume) and survival rates of transplanted bivalves following exposure to Estuary water are evidence that the animals were healthy and capable of bioaccumulation at most sites (Figures 5.17 and 5.18). However, the data on survival and condition of the transplants indicate that certain sites are generating physiological stress in the animals at certain times, which confounds the interpretation of bioaccumulation data and interferes with the bivalves' usefulness as biomonitors.

References

Gunther, A.J. and J.A. Davis. 1997. An evaluation of bioaccumulation monitoring with transplanted bivalves in the RMP. *In* 1996 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. San Francisco Estuary, Richmond, CA pp. 187–200.

Hummel, H., R.H. Bogaards, J. Nieuwenhiuze, L. DeWolf, and J.M. VanLiere. 1990. Spatial and seasonal differences in the PCB content of the mussel *Mytilus edulis*. Science of the Total Environment 92:155–163.

Luoma, S.N. and R. Linville. 1996. A comparison of selenium and mercury concentrations in transplanted and resident bivalves from north San Francisco Bay. *In* 1995 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. San Francisco Estuary, Richmond, CA pp. 160–170.

Martincic, D., Z. Kwokal, Z. Peharec, D. Margus, and M. Branica. 1992. Distribution of Zn, Pb, Cd, and Cu between seawater and transplanted mussels (*Mytilus galloprovinciatis*). Science of the Total Environment 119:211–230.

Phillips, P.T. 1988. California State Mussel Watch ten year data summary, 1977–1987. Water Quality Monitoring Report No. 87-3, Division of Water Quality, State Water Resources Control Board.

Rasmussen, D. 1994. State Mussel Watch Program, 1987–1993 Data Report. State Water Resources Control Board 94-1WQ.

Vinogradov, A.P. 1959. The geochemistry of rare and dispersed chemical elements in soils. Chapman and Hall, London.

Wu, R.S.S. and C.D. Levings. 1980. Mortality, growth and fecundity of transplanted mussel and barnacle populations near a pulp mill outfall. Marine Pollution Bulletin 11:11–15.

Young, D.R., T.C. Heesen, and D.J. McDermott. 1976. An offshore biomonitoring system for chlorinated hydrocarbons. Marine Pollution Bulletin 7:156–159.

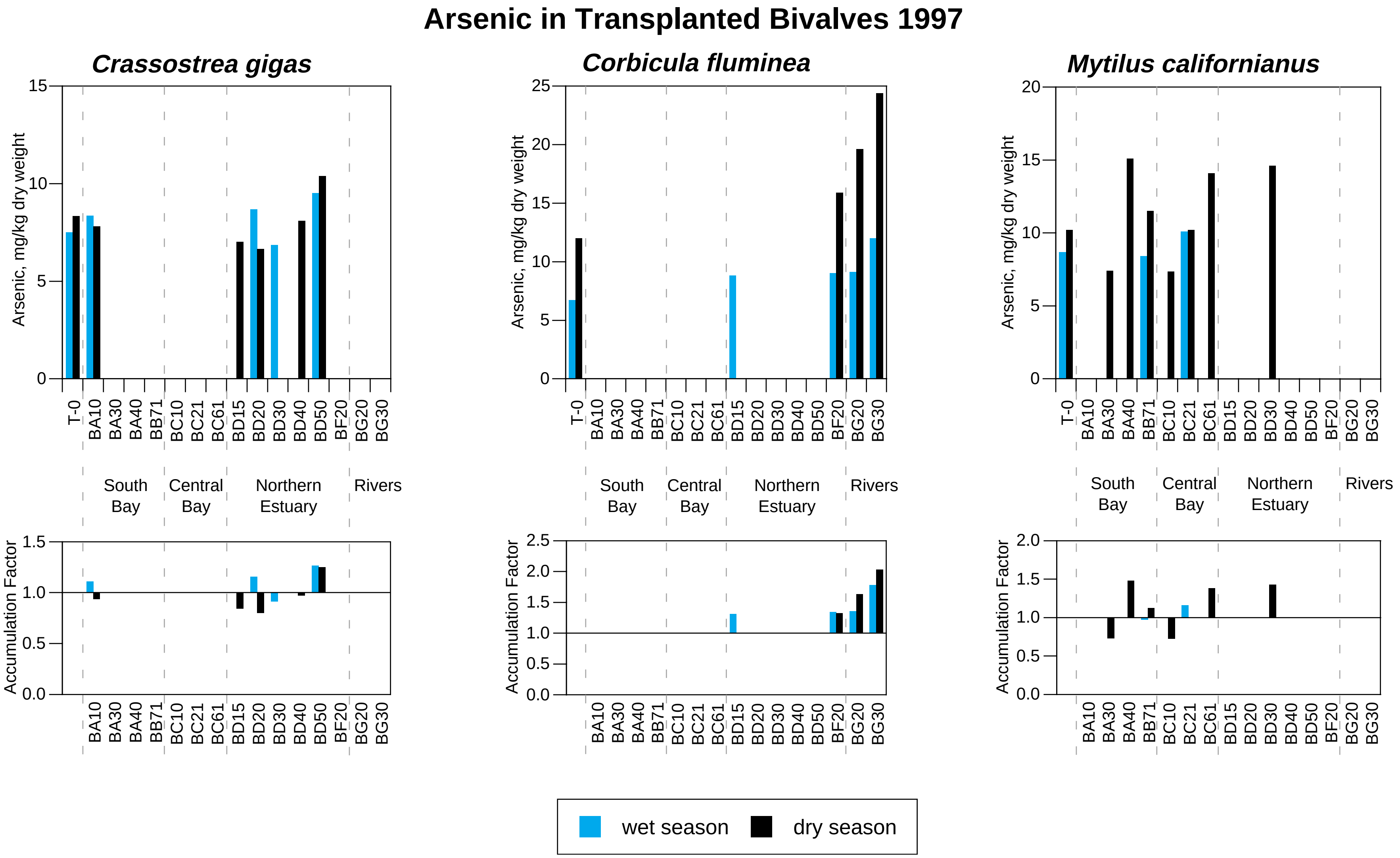

Figure 5.1. Arsenic concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.72 (depuration) to 2.0. Median concentrations were highest in *C. fluminea*, intermediate in *M. californianus*, and lowest in *C. gigas*. The highest measured concentration was in *C. fluminea*, at San Joaquin River (BG30) in the dry season.

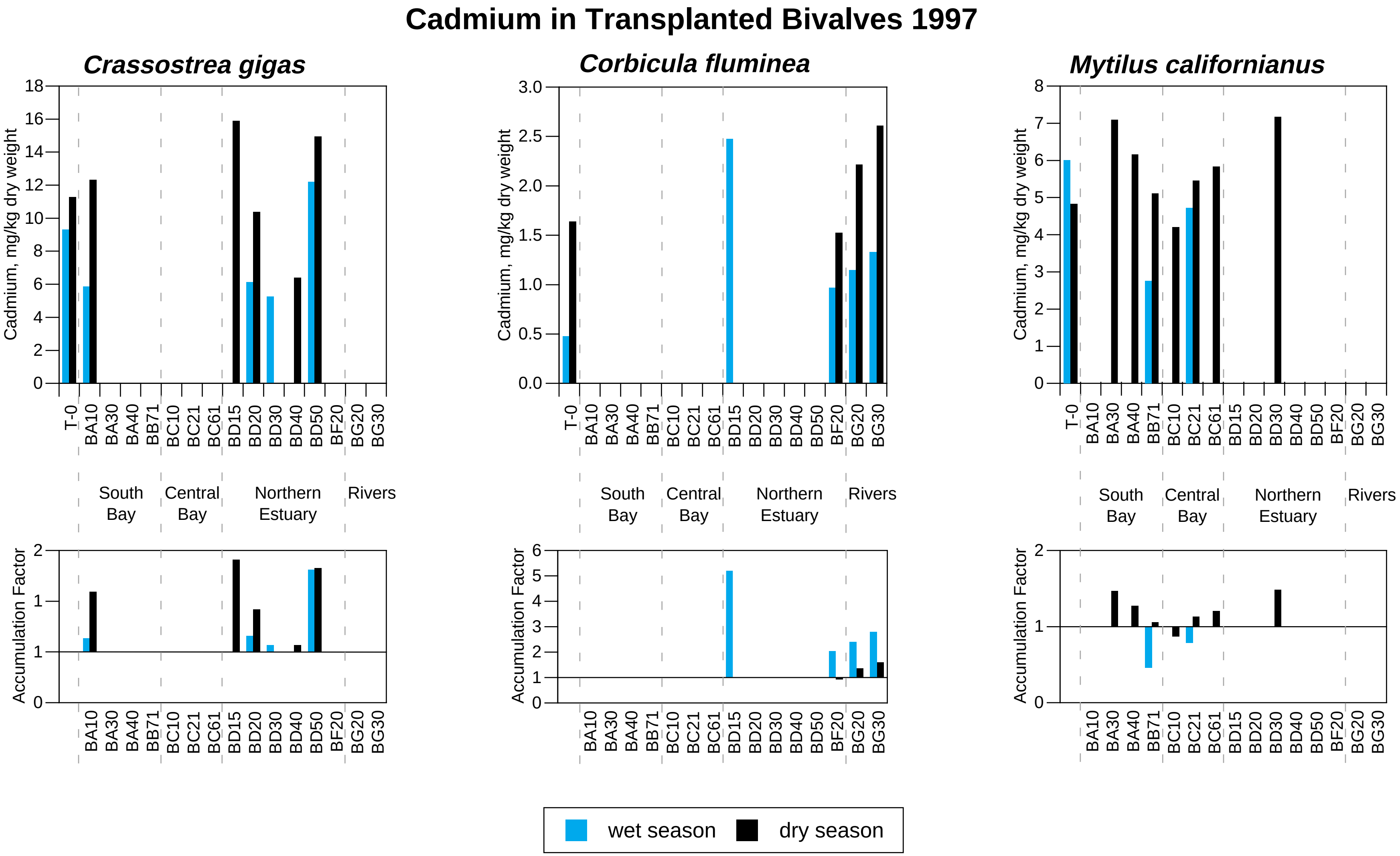

Figure 5.2. Cadmium concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.46 (depuration) to 5.2. Median concentrations were highest in *C. gigas*, intermediate in *M. californianus*, and lowest in *C. fluminea*. The highest measured concentration was in *C. gigas*, at Petaluma River (BD15) in the dry season.

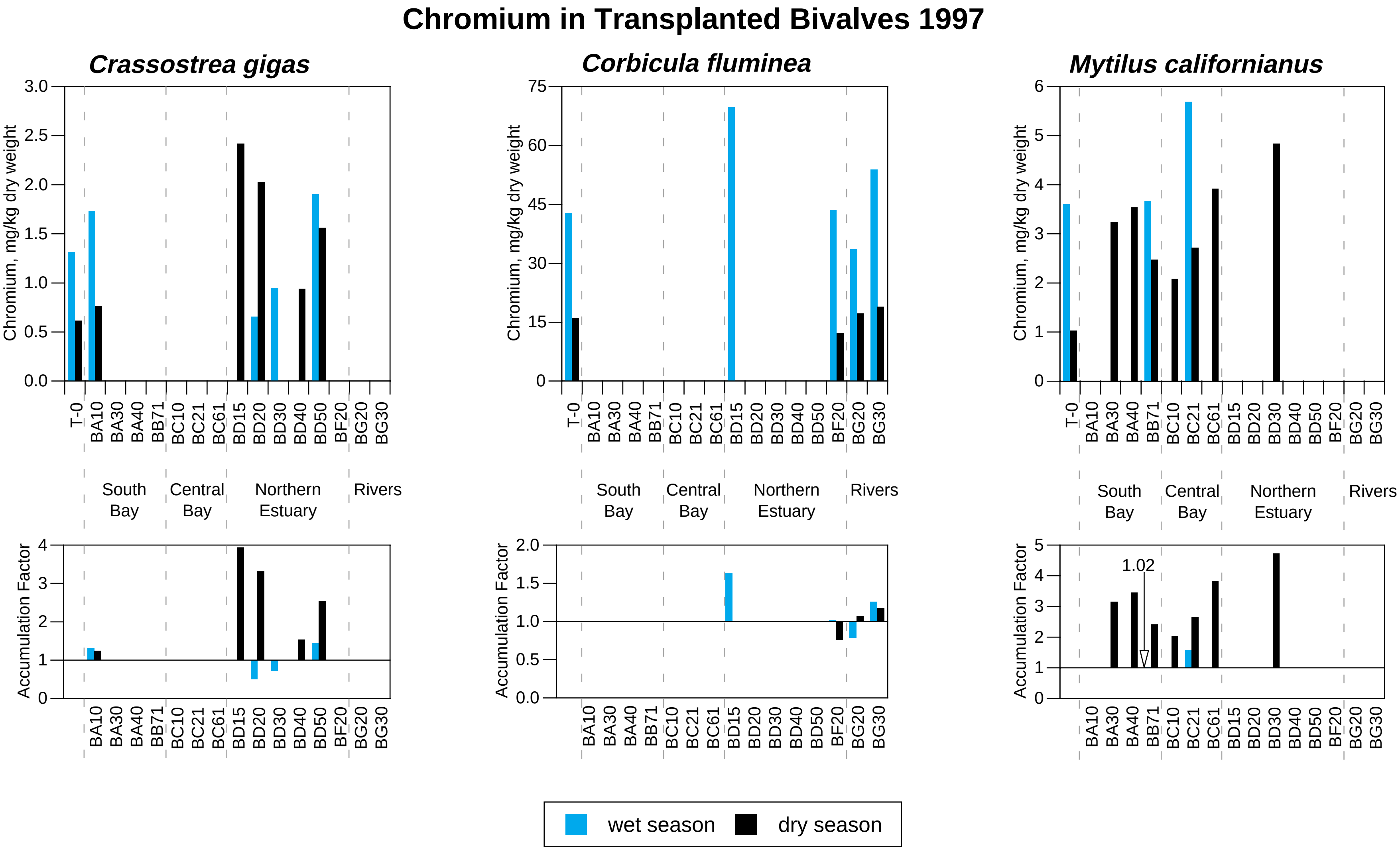

Figure 5.3. Chromium concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.5 (depuration) to 4.7. Median concentrations were highest in *C. fluminea*, intermediate in *M. californianus*, and lowest in *C. gigas*. The highest measured concentration was in *C. fluminea*, at Petaluma River (BD15) in the wet season.

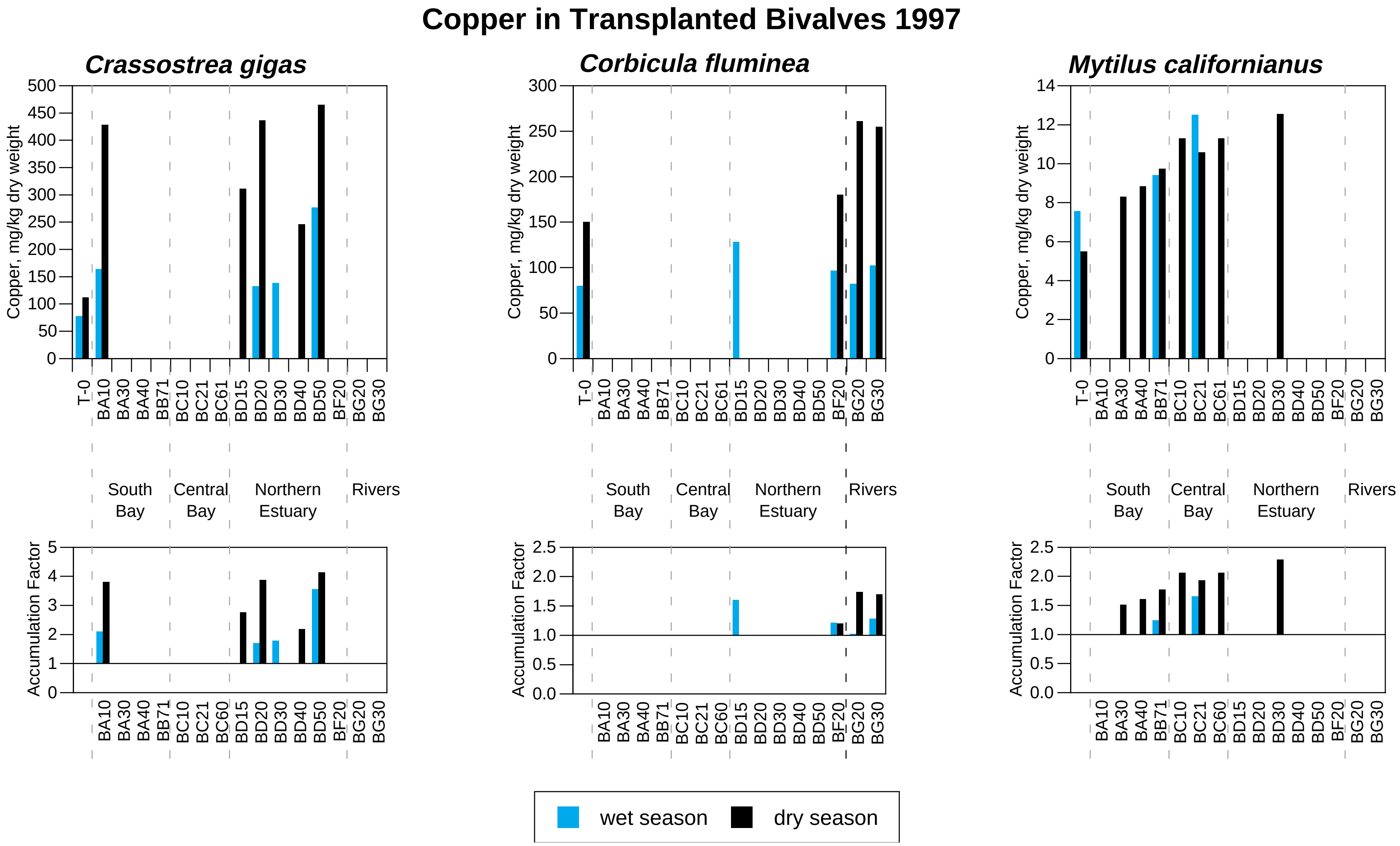

Figure 5.4. Copper concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 1.02 to 4.1. Median concentrations were highest in *C. gigas*, intermediate in *C. fluminea*, and lowest in *M. californianus*. The highest measured concentration was in *C. gigas*, at Napa River (BD50) in the dry season.

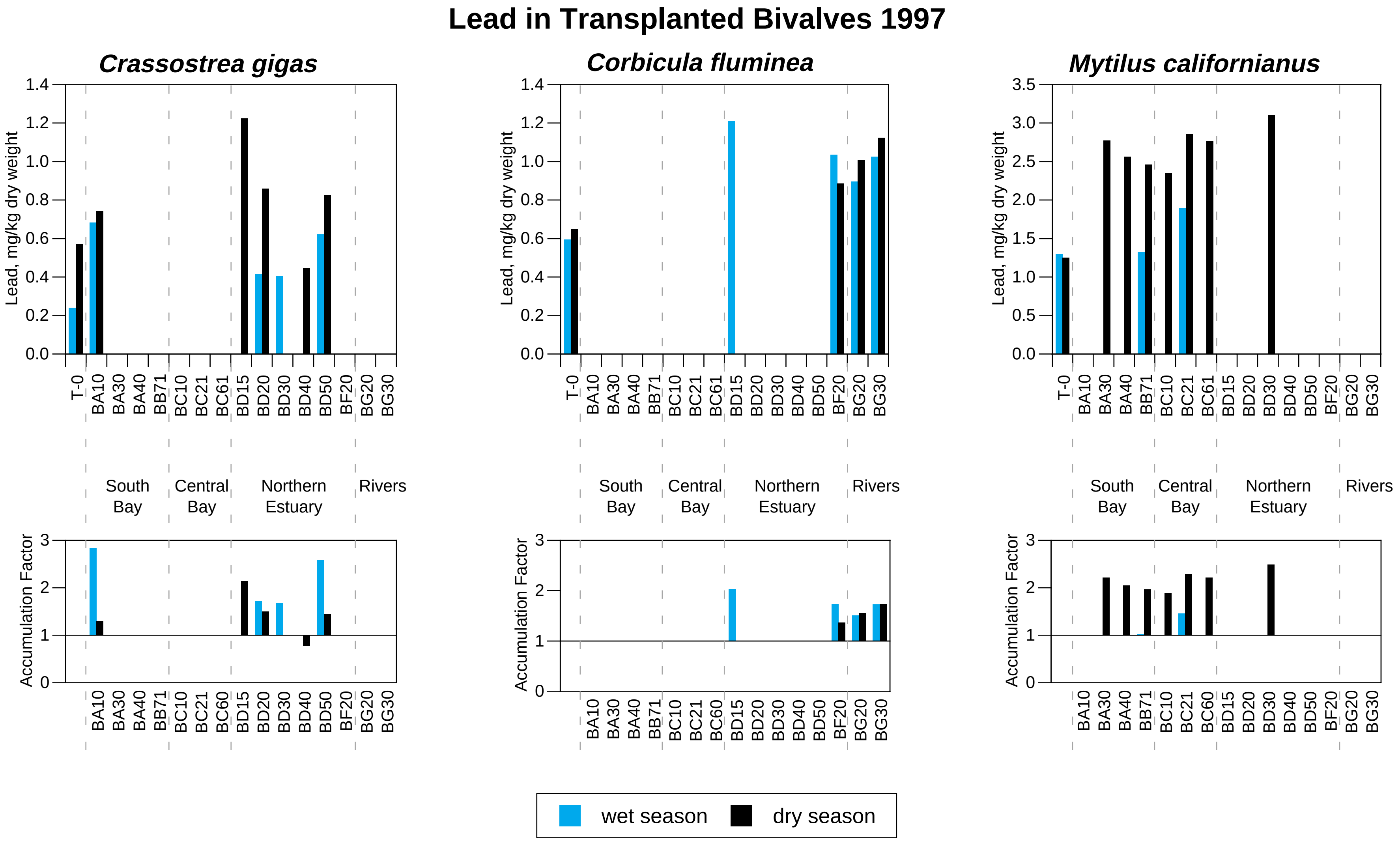

Figure 5.5. Lead concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.8 (depuration) to 2.8. Median concentrations were highest in *M. californianus*, intermediate in *C. fluminea*, and lowest in *C. gigas*. The highest measured concentration was in *M. californianus*, at Pinole Point (BD30) in the dry season.

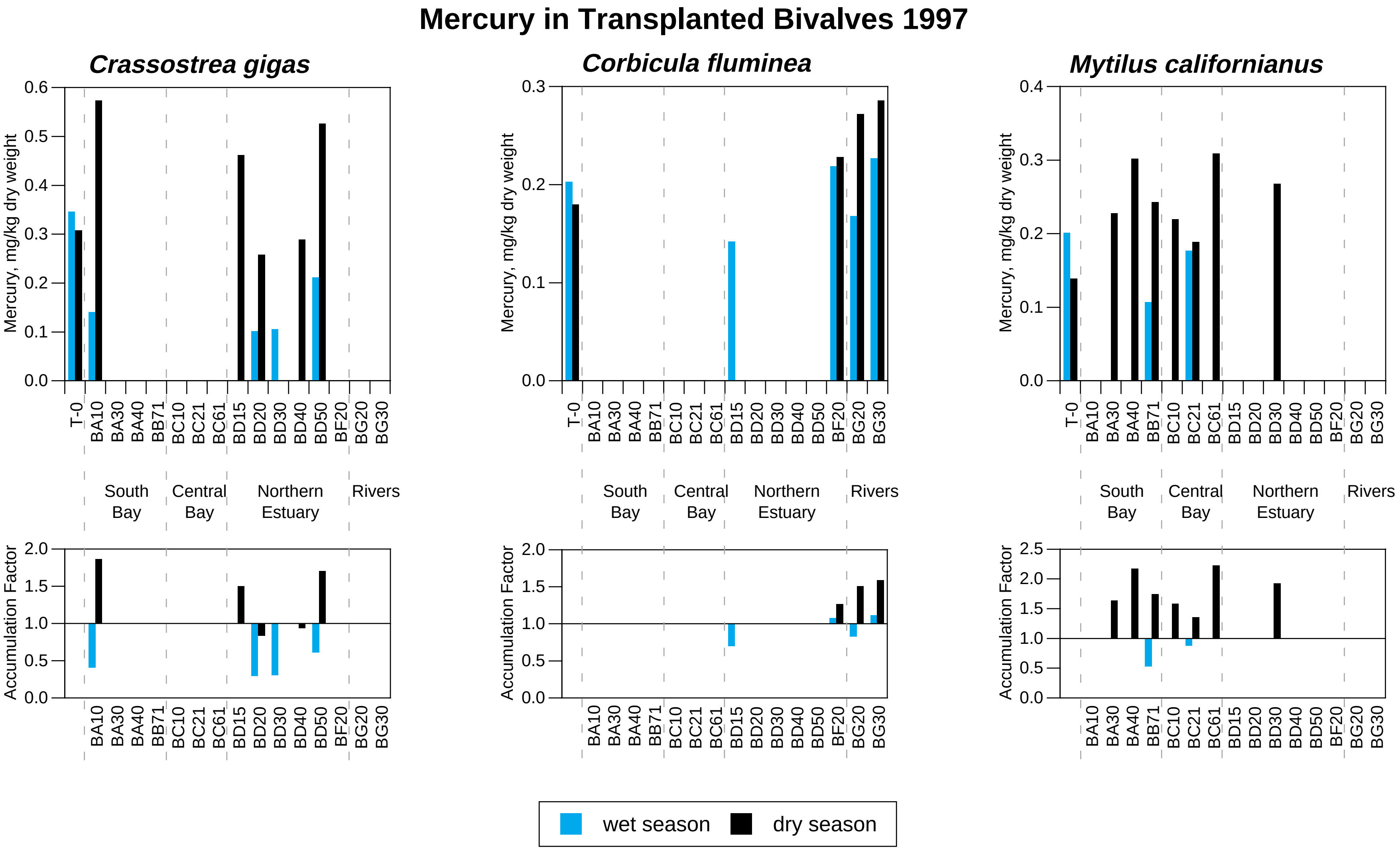

Figure 5.6. Mercury concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.3 (depuration) to 2.2. Median concentrations were highest in *C. fluminea*, intermediate in *M. californianus*, and lowest in *C. gigas*. The highest measured concentration was in *C. gigas*, at Coyote Creek (BA10) in the dry season. All stations had tissue concentrations much lower than the implicit tissue guideline of 7 ppm used to calculate water quality objectives in the draft California Toxics Rule.

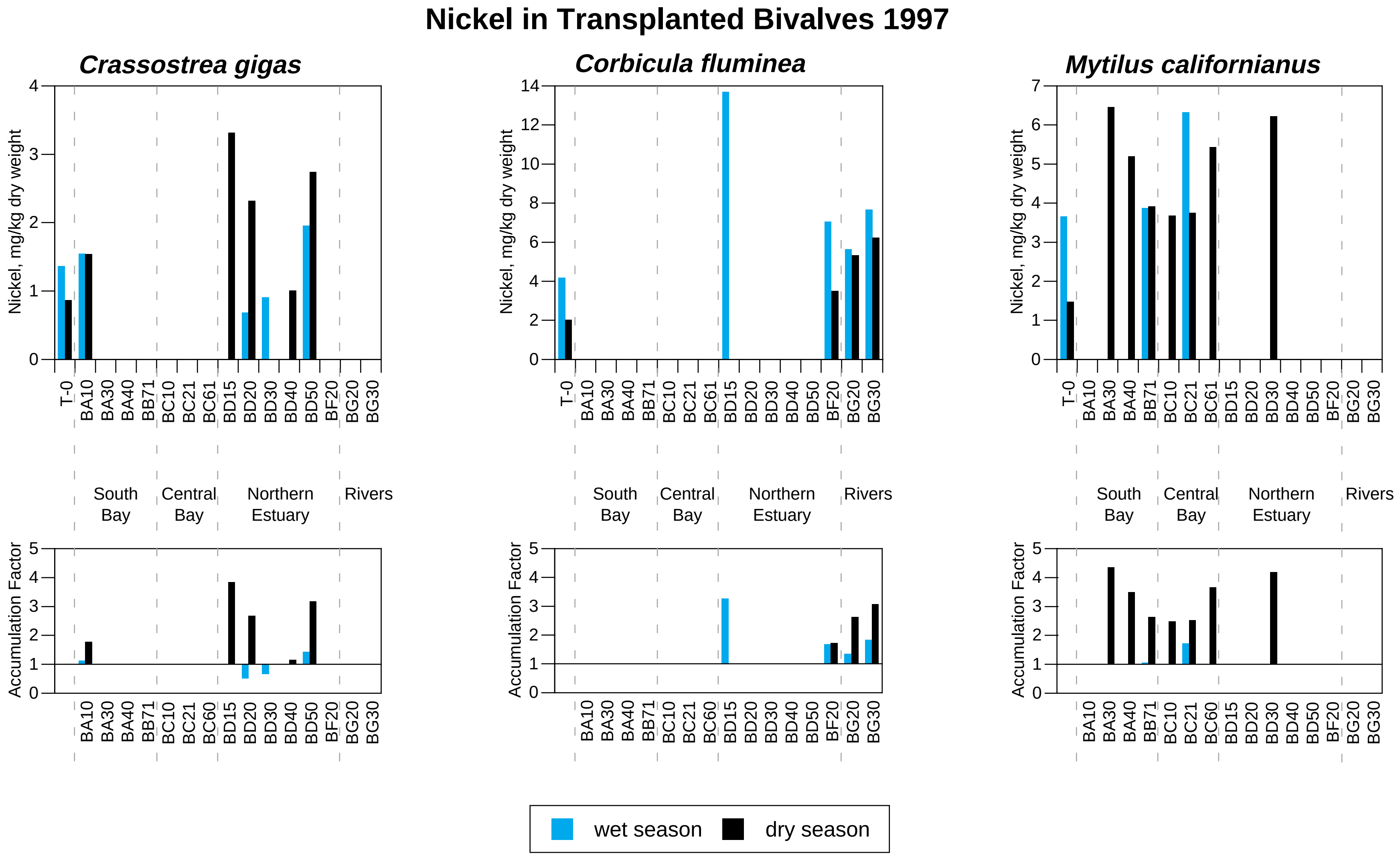

Figure 5.7. Nickel concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.5 (depuration) to 4.4. Median concentrations were highest in *C. fluminea*, intermediate in *M. californianus*, and lowest in *C. gigas*. The highest measured concentration was in *C. fluminea*, at Petaluma River (BD15) in the wet season. No samples exceeded the proposed California Toxics Rule's implicit tissue guideline of 215.4 ppm.

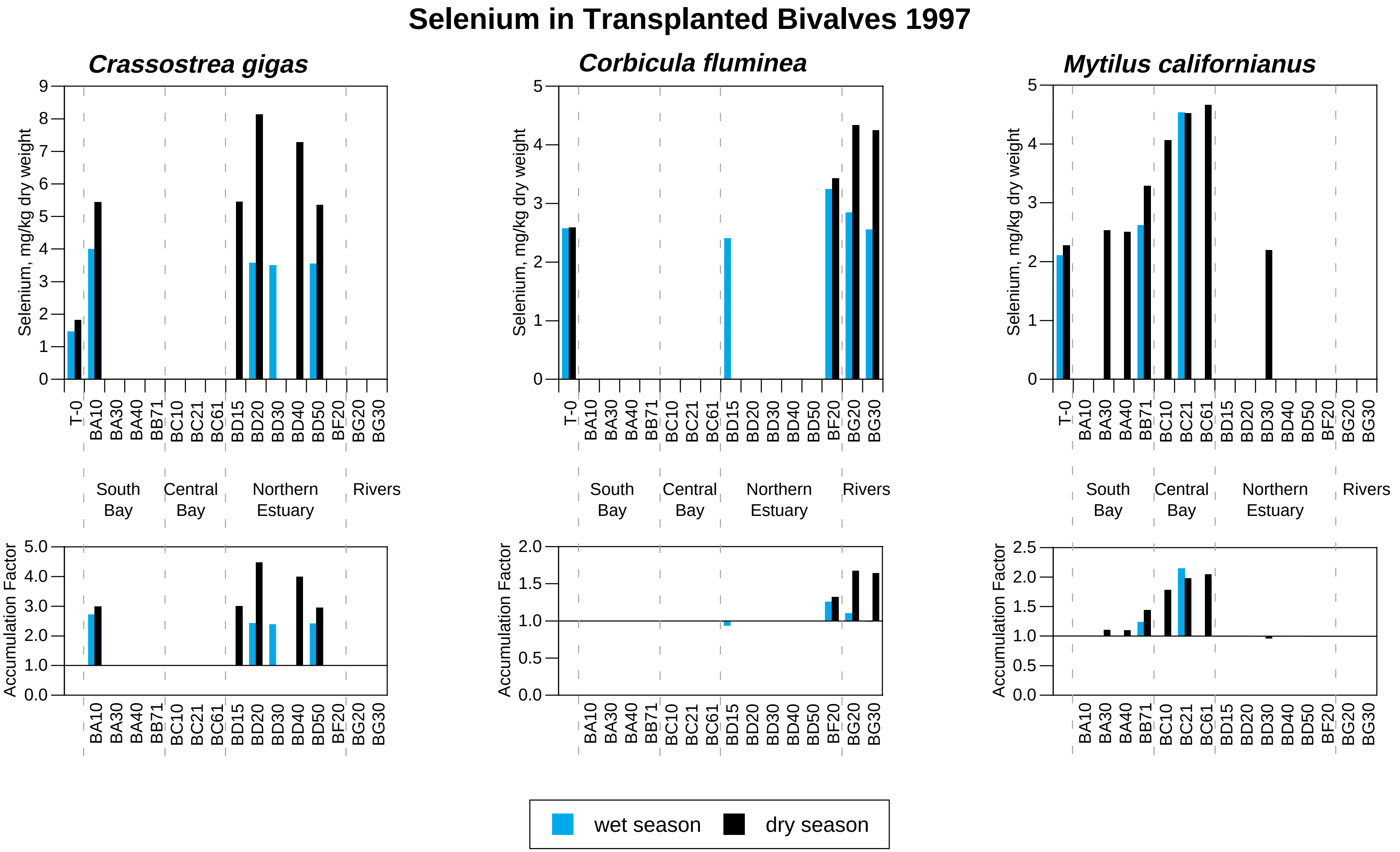

Figure 5.8. Selenium concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.93 (depuration) to 4.5. Median concentrations were highest in *C. gigas*, intermediate in *M. californianus*, and lowest in *C. fluminea*. The highest measured concentration was in *C. gigas*, at San Pablo Bay (BD20) in the dry season.

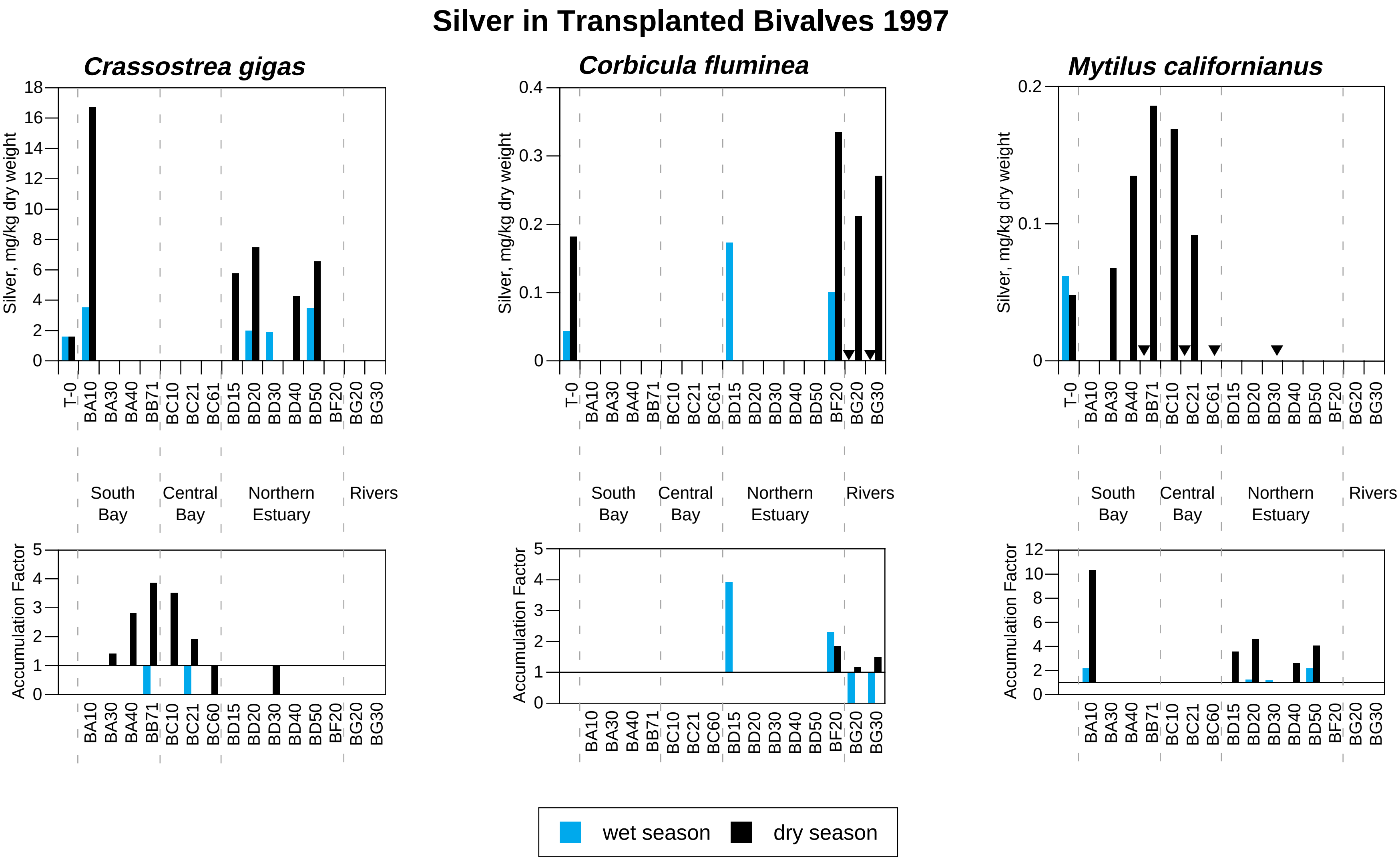

Figure 5.9. Silver concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. ▼ = not detected. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.008 (depuration) to 10.3. Median concentrations were highest in *C. gigas*, intermediate in *C. fluminea*, and lowest in *M. californianus*. The highest measured concentration was in *C. gigas*, at Coyote Creek (BA10) in the dry season. Eleven stations, including two of the reference samples, had concentrations exceeding the proposed California Toxics Rule's implicit tissue guideline of 1 ppm. For calculations, non-detects were substituted with half the target method detection (MDL) listed in the 1996 Quality Assurance Project Plan (Lowe *et al.*, 1996).

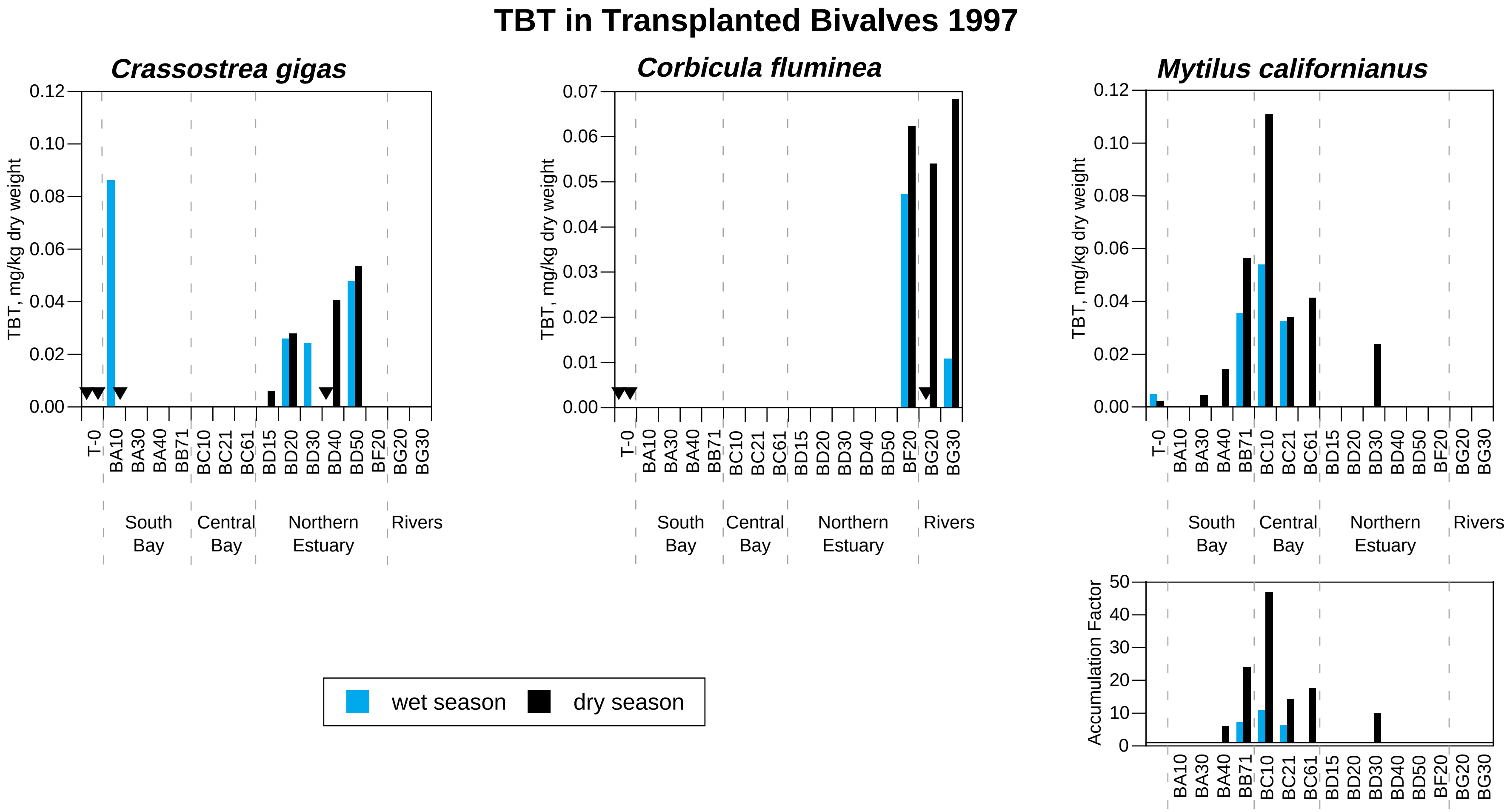

Figure 5.10. Tributyltin concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. ▼ = not detected. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 1.9 to 47.0. Accumulation factors were not calculated for *C. gigas* and *C. fluminea* because T-0 concentrations for both the wet and dry seasons were not detected. Median concentrations were highest in *C. fluminea*, intermediate in *M. californianus*, and lowest in *C. gigas*. The highest measured concentration was in *M. californianus*, at Yerba Buena Island (BC10) in the dry season.

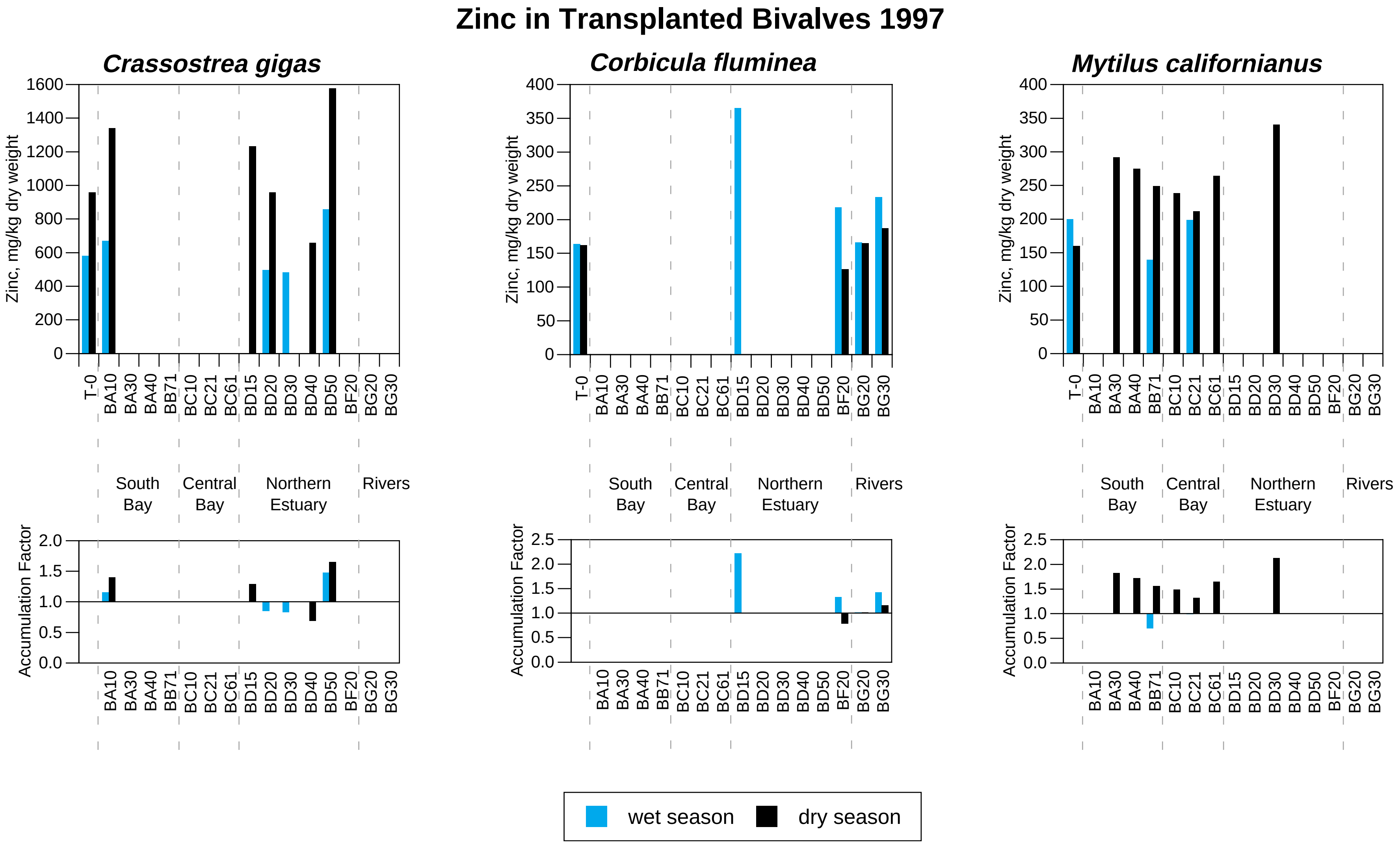

Figure 5.11. Zinc concentrations in parts per million dry weight (ppm) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.69 (depuration) to 2.2. Median concentrations were highest in *C. gigas*, intermediate in *M. californianus*, and lowest in *C. fluminea*. The highest measured concentration was in *C. gigas*, at Napa River (BD50) in the dry season.

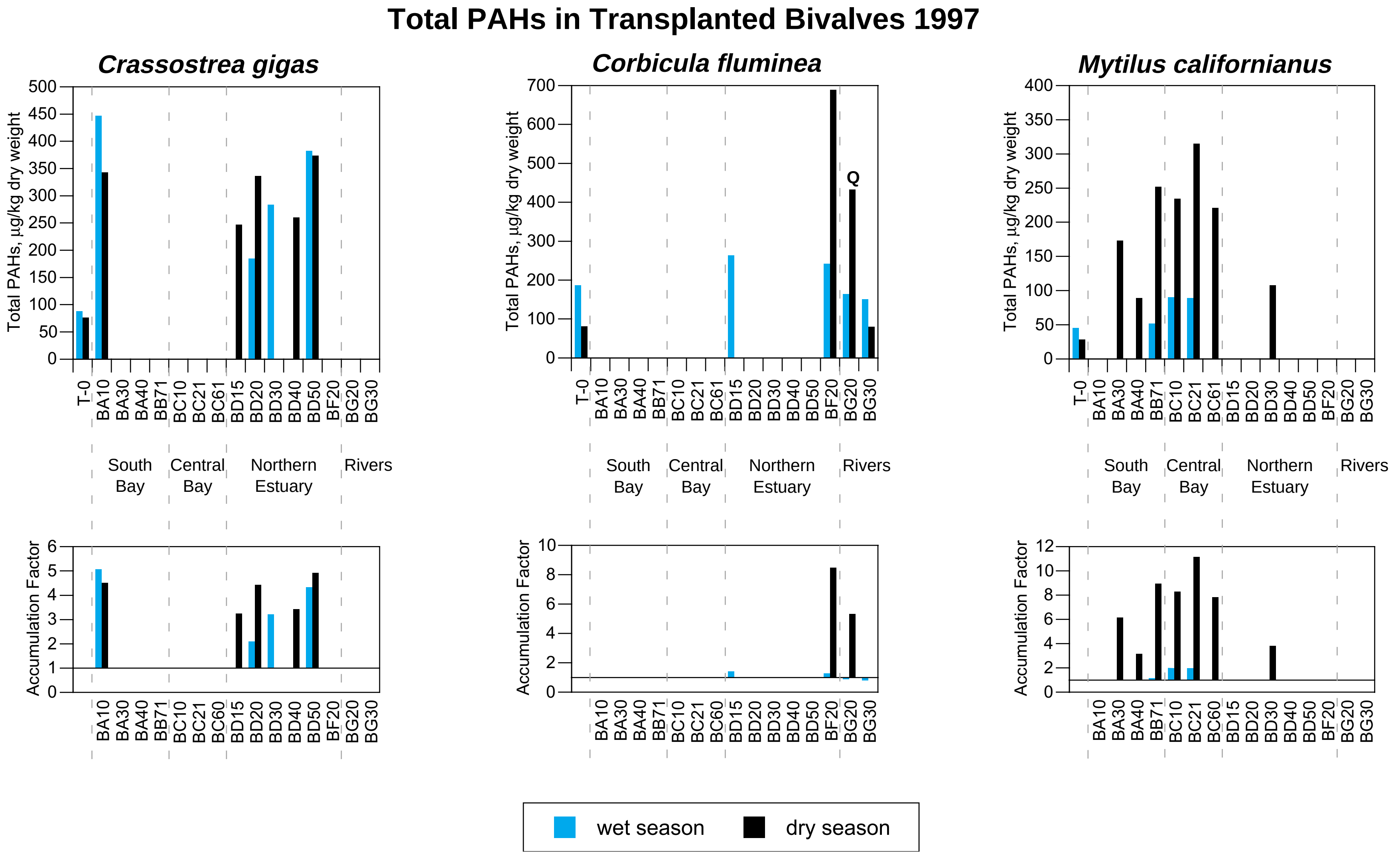

Figure 5.12. Total PAH concentrations in parts per billion dry weight (ppb) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. Q = data point outside data quality objectives. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.8 (depuration) to 11.2. Median concentrations were highest in *C. gigas*, intermediate in *C. fluminea*, and lowest in *M. californianus*. The highest measured concentration was in *C. fluminea*, at Grizzly Bay (BF20) in the dry season. Implicit tissue guidelines embedded in the proposed California Toxics Rule only exist for selected PAH compounds.

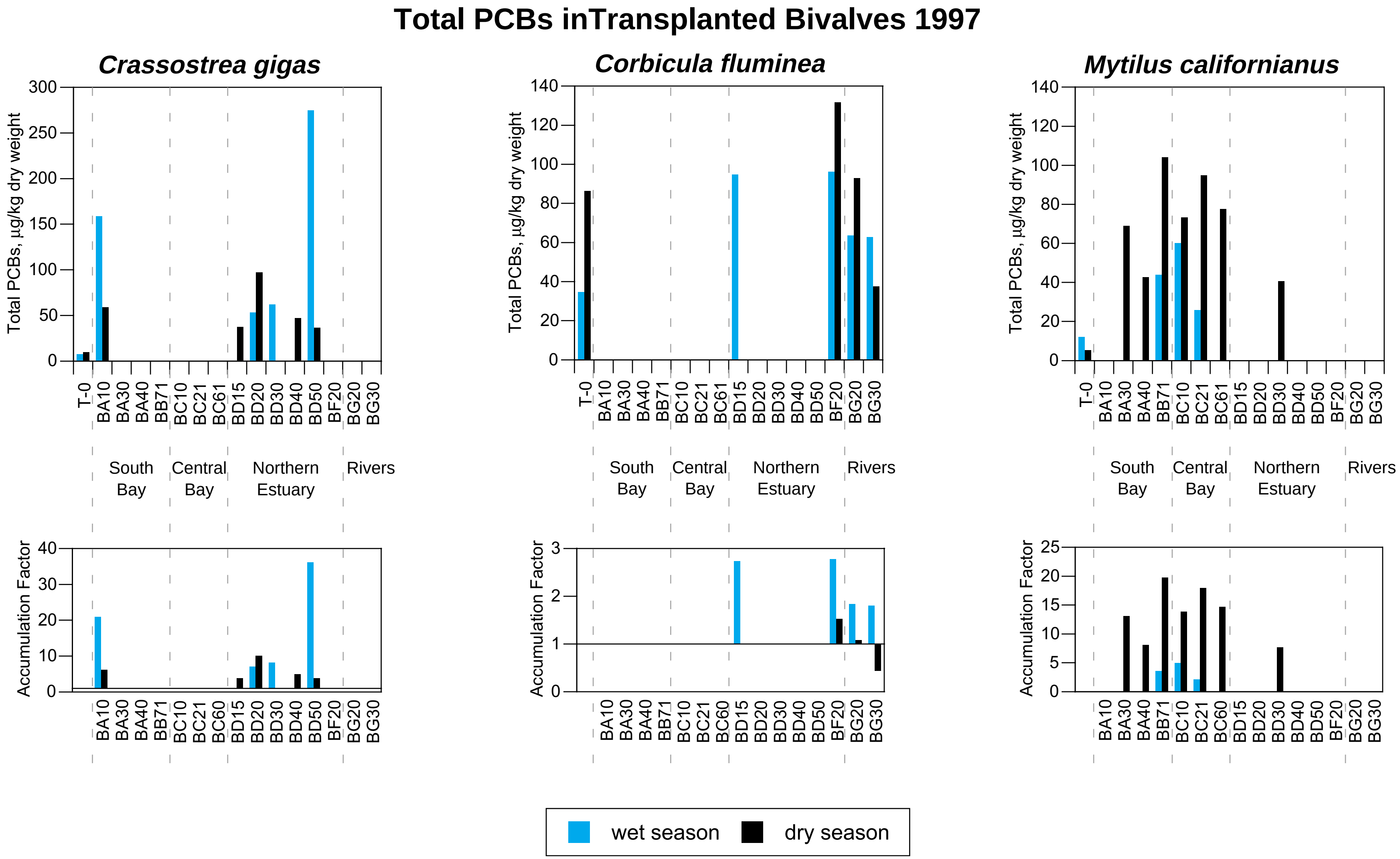

Figure 5.13. Total PCB concentrations in parts per billion dry weight (ppb) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.4 (depuration) to 36.2. Median concentrations were highest in *C. fluminea*, intermediate in *M. californianus*, and lowest in *C. gigas*. The highest measured concentration was in *C. gigas*, at Napa River (BD50) in the wet season. All samples, including reference samples, had total PCB concentrations exceeding the proposed California Toxics Rule's implicit tissue guideline of 1.4 ppb (total Aroclors).

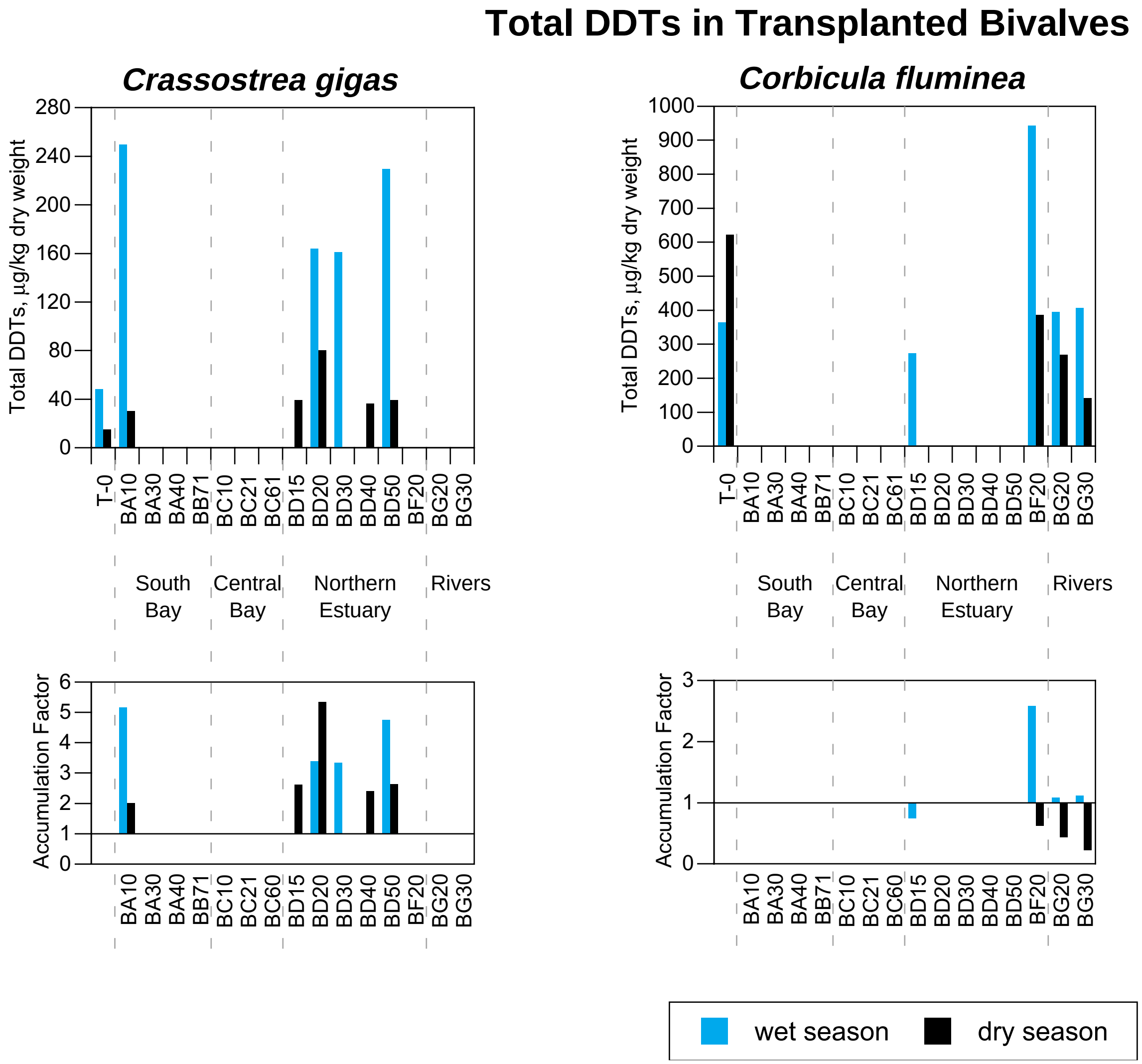

Figure 5.14. Total DDT concentrations in parts per billion dry weight (ppb) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.2 (depuration) to 9.0. Median concentrations were highest in *C. fluminea*, intermediate in *C. gigas*, and lowest in *M. californianus*. The highest measured concentration was in *C. fluminea*, at Grizzly Bay (BF20) in the wet season. Sixteen samples, including three reference samples, exceeded the proposed California Toxics Rule's (CTR) implicit tissue guideline for p,p'-DDT of 3.16 ppb. All samples, including reference samples, exceeded the tissue guideline for p,p'-DDE of 3.16 ppb. Seven samples, including one reference sample, exceeded tissue guideline for p,p'-DDD of 44.9 ppb (see Table 21, *Appendix C*).

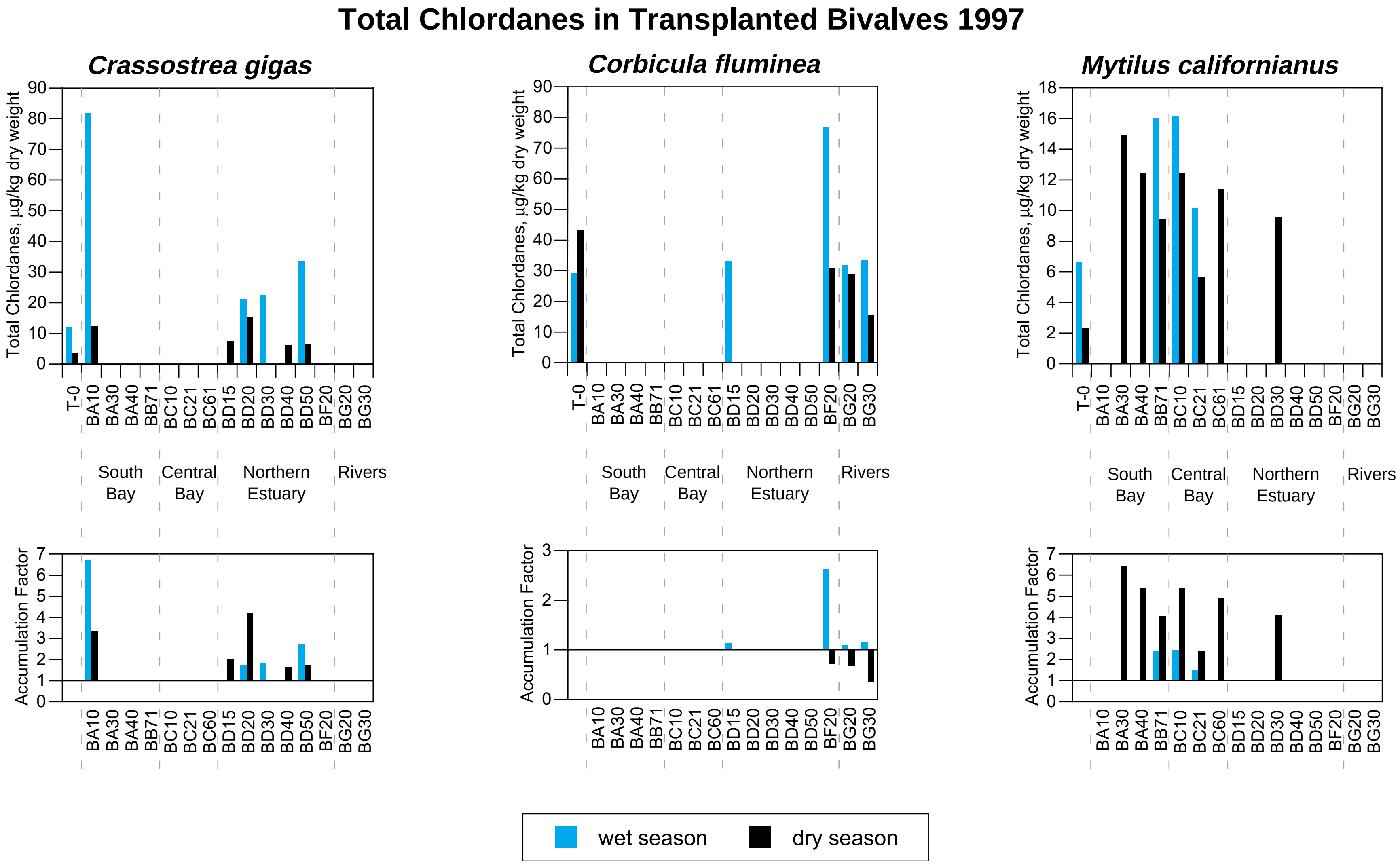

Figure 5.15. Total chlordane concentrations in parts per billion dry weight (ppb) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 0.4 (depuration) to 6.7. Median concentrations were highest in *C. fluminea*, intermediate in *C. gigas*, and lowest in *M. californianus*. The highest measured concentration was in *C. gigas*, at Coyote Creek (BA10) in the wet season. Twenty-five samples, including three of the reference samples, had chlordane concentrations exceeding the proposed California Toxics Rule's implicit tissue guideline of 8.3 ppb.

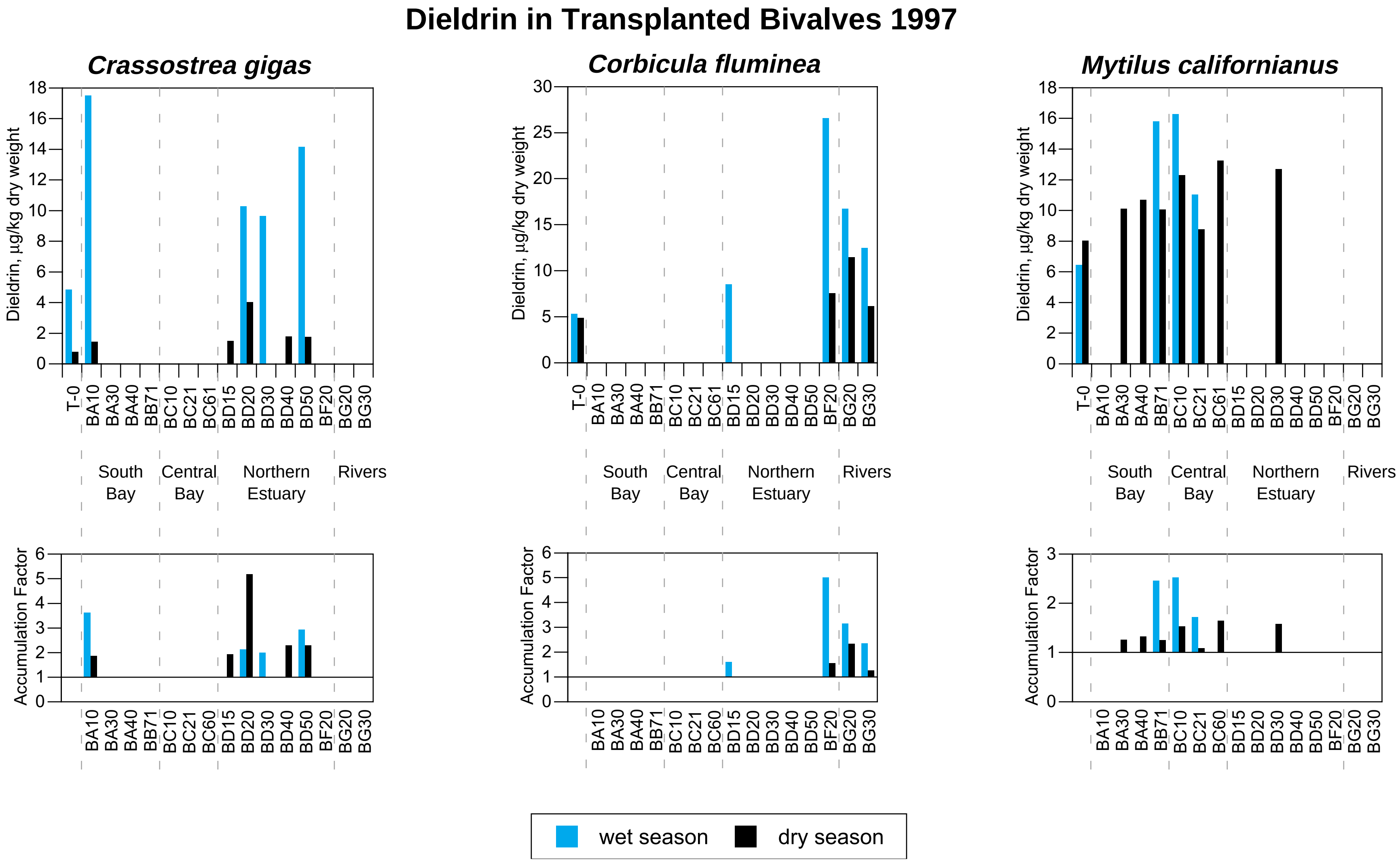

Figure 5.16. Dieldrin concentrations in parts per billion dry weight (ppb) in three transplanted bivalve species at 15 RMP stations during the wet- and dry-season sampling periods. There were no samples for Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) in the wet season due to zero percent species survival. Bivalves were not deployed at Davis Point (BD40) in the wet season. T-0 (time zero) is the initial concentration before deployment in the Estuary. Accumulation factors ranged from 1.1 to 5.2. Median concentrations were highest in *M. californianus*, intermediate in *C. fluminea*, and lowest in *C. gigas*. The highest measured concentration was in *C. fluminea*, at Grizzly Bay (BF20) in the wet season. All samples, including the reference samples, had dieldrin concentrations exceeding the proposed California Toxics Rule's implicit tissue guideline of 0.67 ppb.

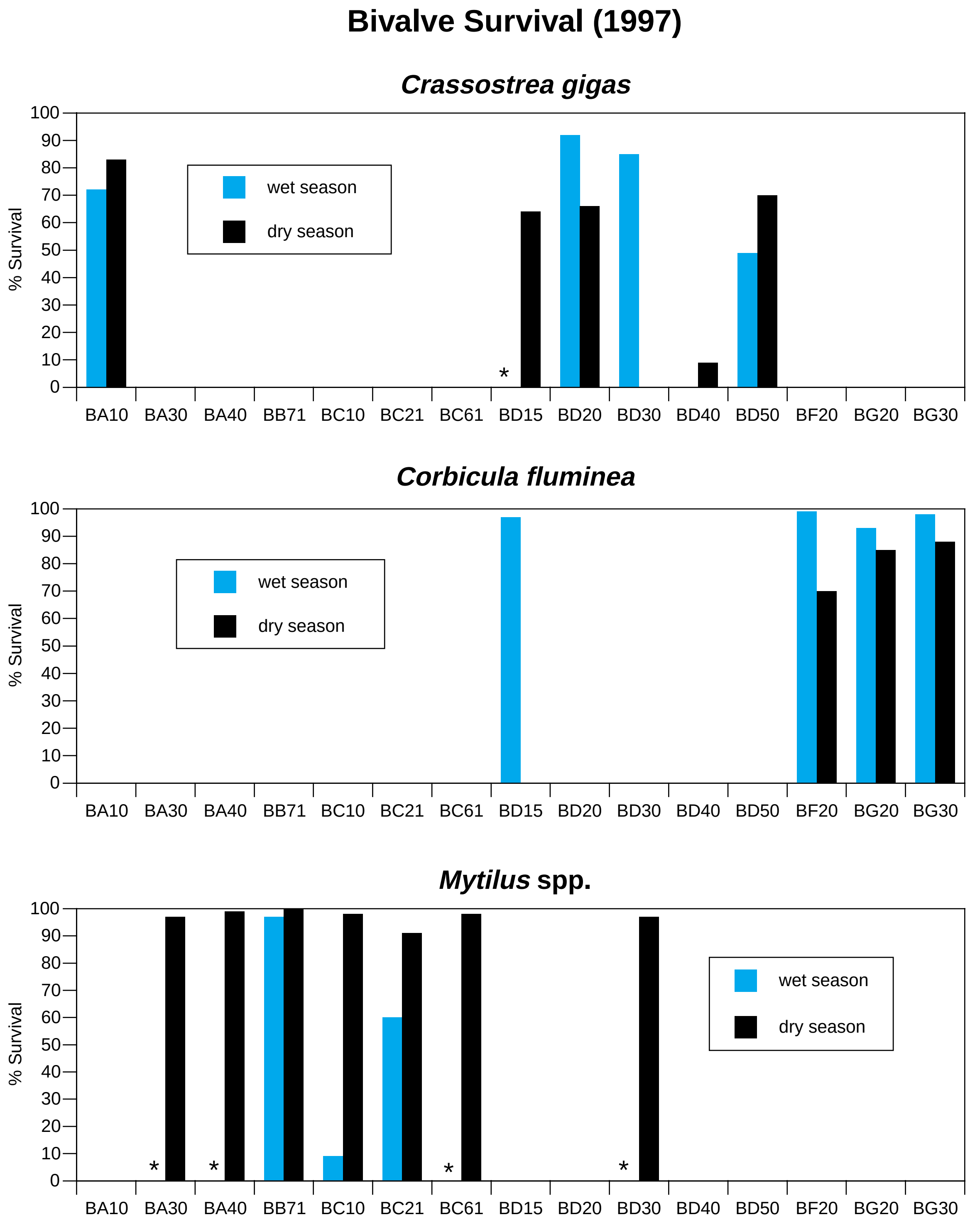

Figure 5.17. Percent survival of transplanted bivalves following exposure to Estuary conditions during the wet (May) and dry season (September) of 1997. * indicates 0% survival.

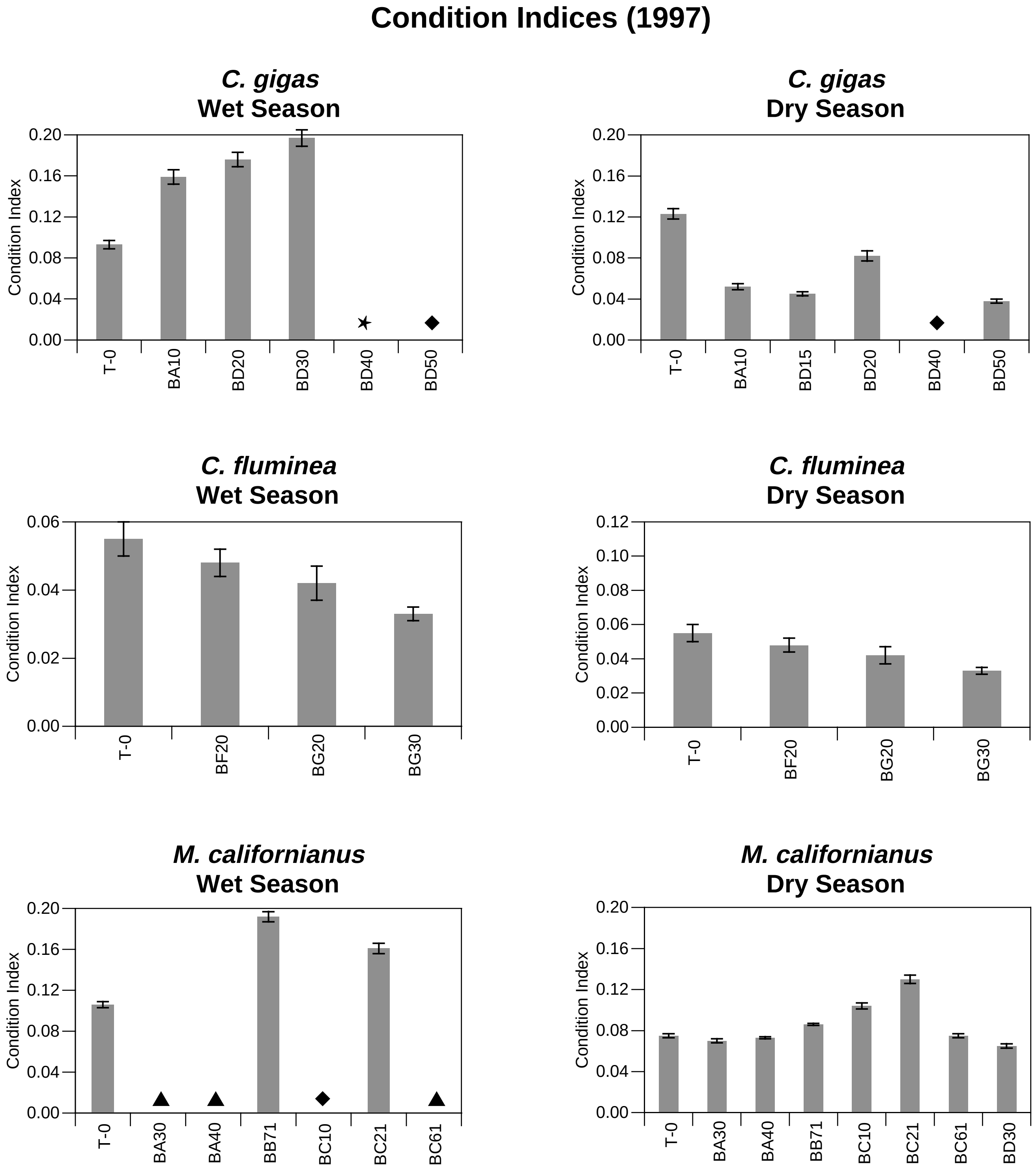

Figure 5.18. Condition indices of three species of bivalves at their original "reference" locations, prior to deployment (T-0), and at the end of their exposure to San Francisco Estuary waters (various locations) during the wet and dry seasons of 1997. Bivalves deployed at the Dumbarton Bridge (BA30), Redwood Creek (BA40), and Red Rock (BC61) stations during the wet season did not survive (indicated by ▲). Bivalves were not deployed at the Davis Point (BD50) station in the wet season (indicated by ✶). Surviving bivalves retrieved from the Napa River (BD50) and Yerba Buena Island (BC10) stations during the wet season and the Davis Point (BD40) station during the dry season were allocated to trace elements and organics analyses (indicated by ◆). Bars indicate range of values.

Bivalve Monitoring Trends

Transplanted bivalves are valuable in assessment of long-term trends because they provide an integrated measure of contamination over a three month period. This interval is more appropriate for assessment of interannual trends than the one-hour interval represented by RMP water samples or the approximate 20 year interval represented by RMP sediment samples.

This section presents plots of RMP bivalve bioaccumulation data for trace elements and trace organics from 1993 to 1997 (Figures 5.19 and 5.20). Concentrations in these plots are expressed as net bioaccumulation or depuration during the deployment period (initial concentrations prior to deployment have been subtracted from final concentrations measured after deployment). Presented in this manner, the plots are capable of showing the presence or absence of both trends and accumulation during deployment. In many cases (e.g., arsenic) there was either little accumulation or even net depuration during deployment. Mercury in clams has exhibited a consistent seasonal pattern, with higher concentrations in summer samples in all five years. The trace metals database accumulated so far is fairly noisy, and clear trends are not expected to be discernible for the near future.

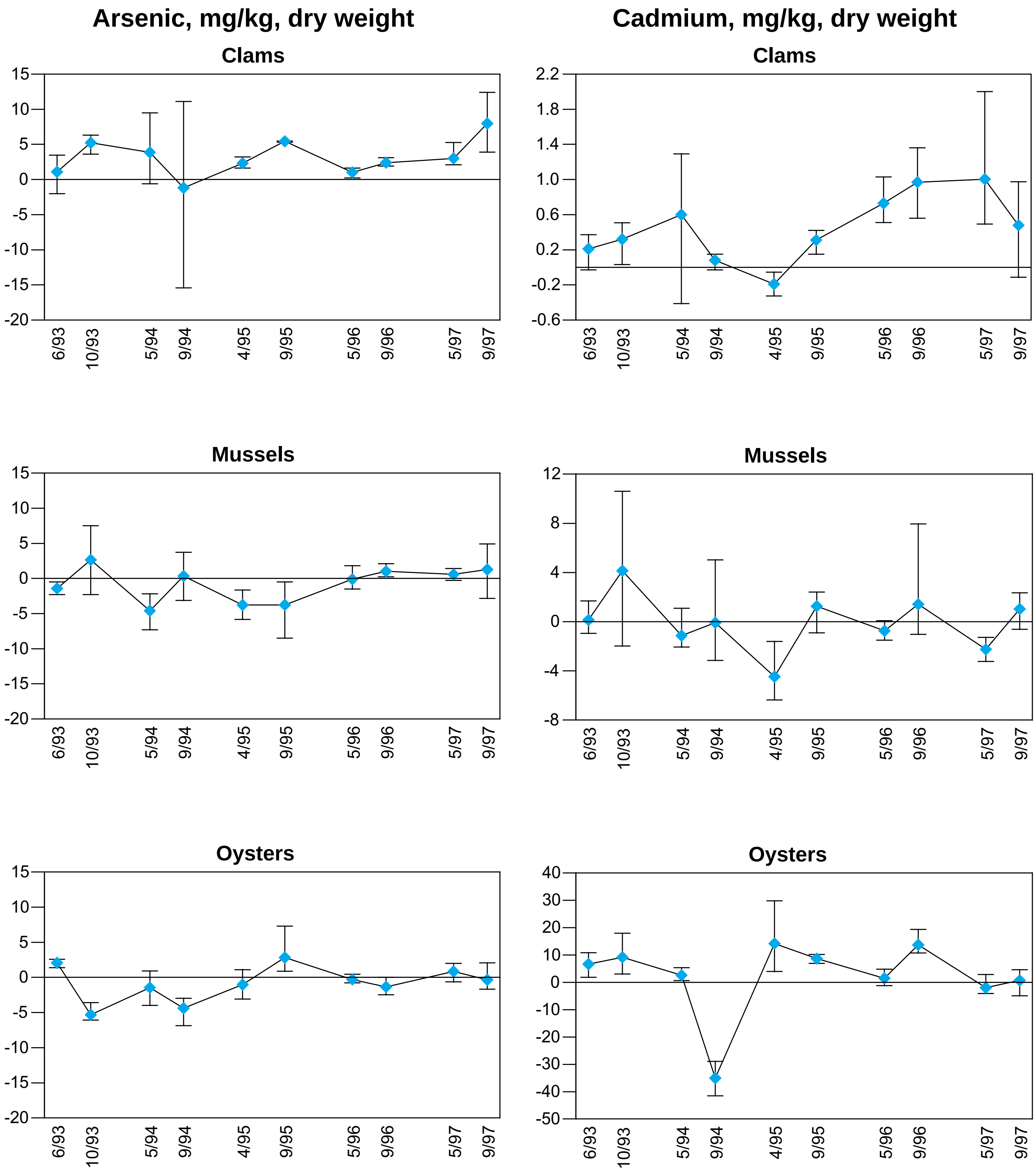

Figure 5.19. Trace element accumulation or depuration in parts per million dry weight (ppm) in three transplanted bivalve species for ten sampling periods from 1993–1997. Initial (T-0) concentrations are subtracted from tissue concentrations after retrieval to give concentrations accumulated or depurated (negative value) during deployment in the Estuary. Bars indicate the range of values of all stations where species were deployed. Note different y-axis scales.

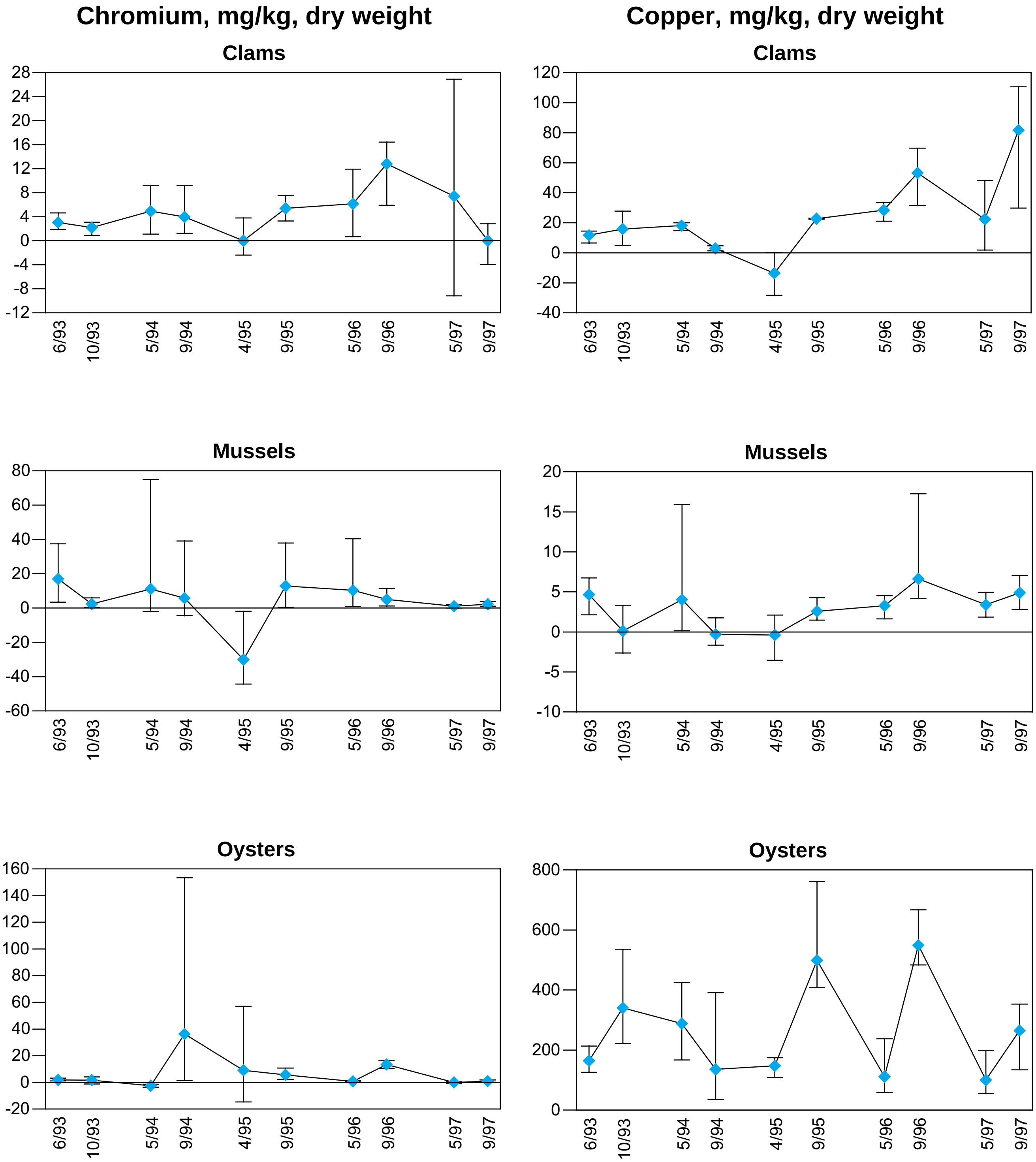

Figure 5.19 (continued). Trace element accumulation or depuration in parts per million dry weight (ppm) in three transplanted bivalve species for ten sampling periods from 1993–1997. Note different y-axis scales.

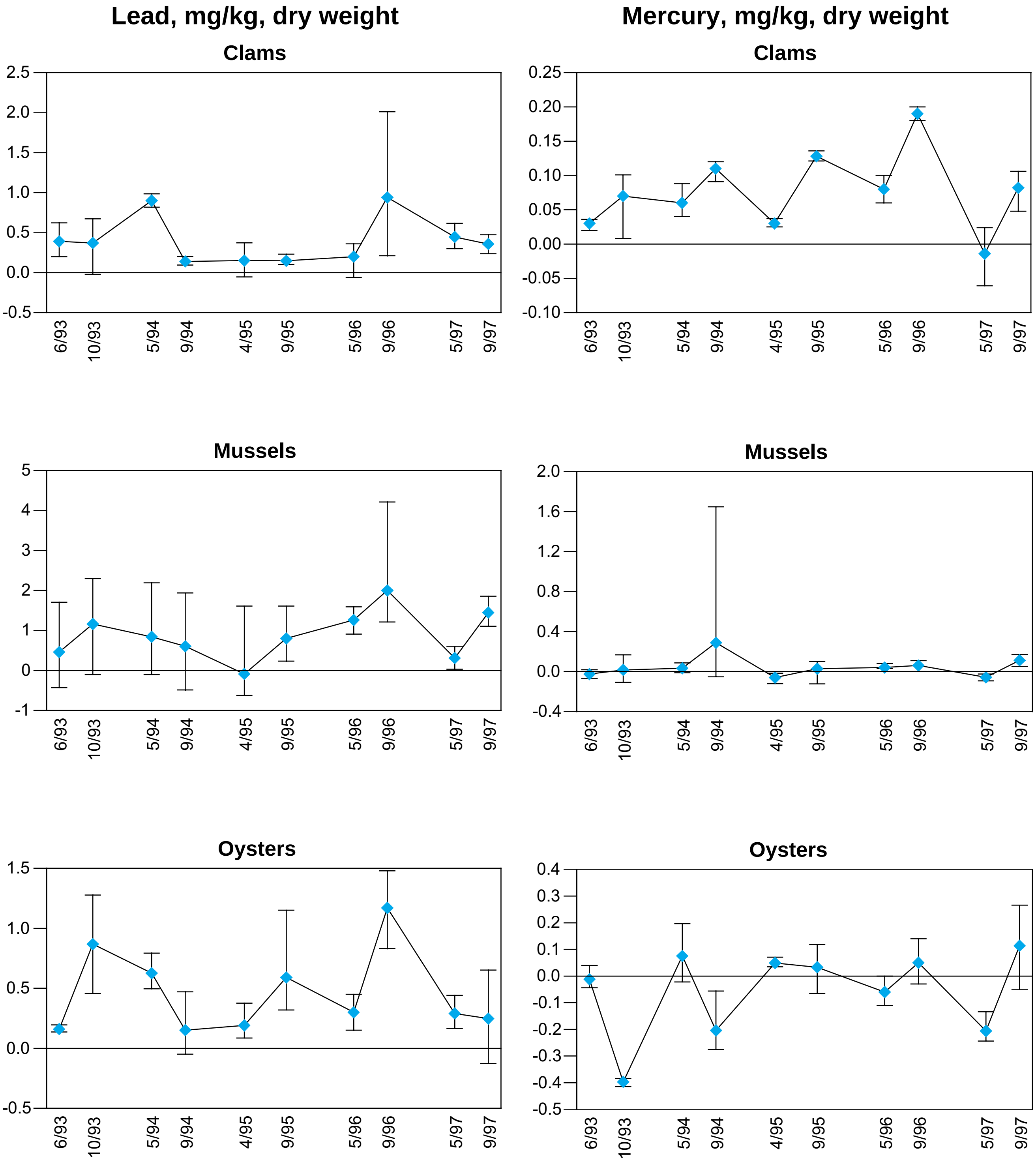

Figure 5.19 (continued). Trace element accumulation or depuration in parts per million dry weight (ppm) in three transplanted bivalve species for ten sampling periods from 1993–1997. Note different y-axis scales.

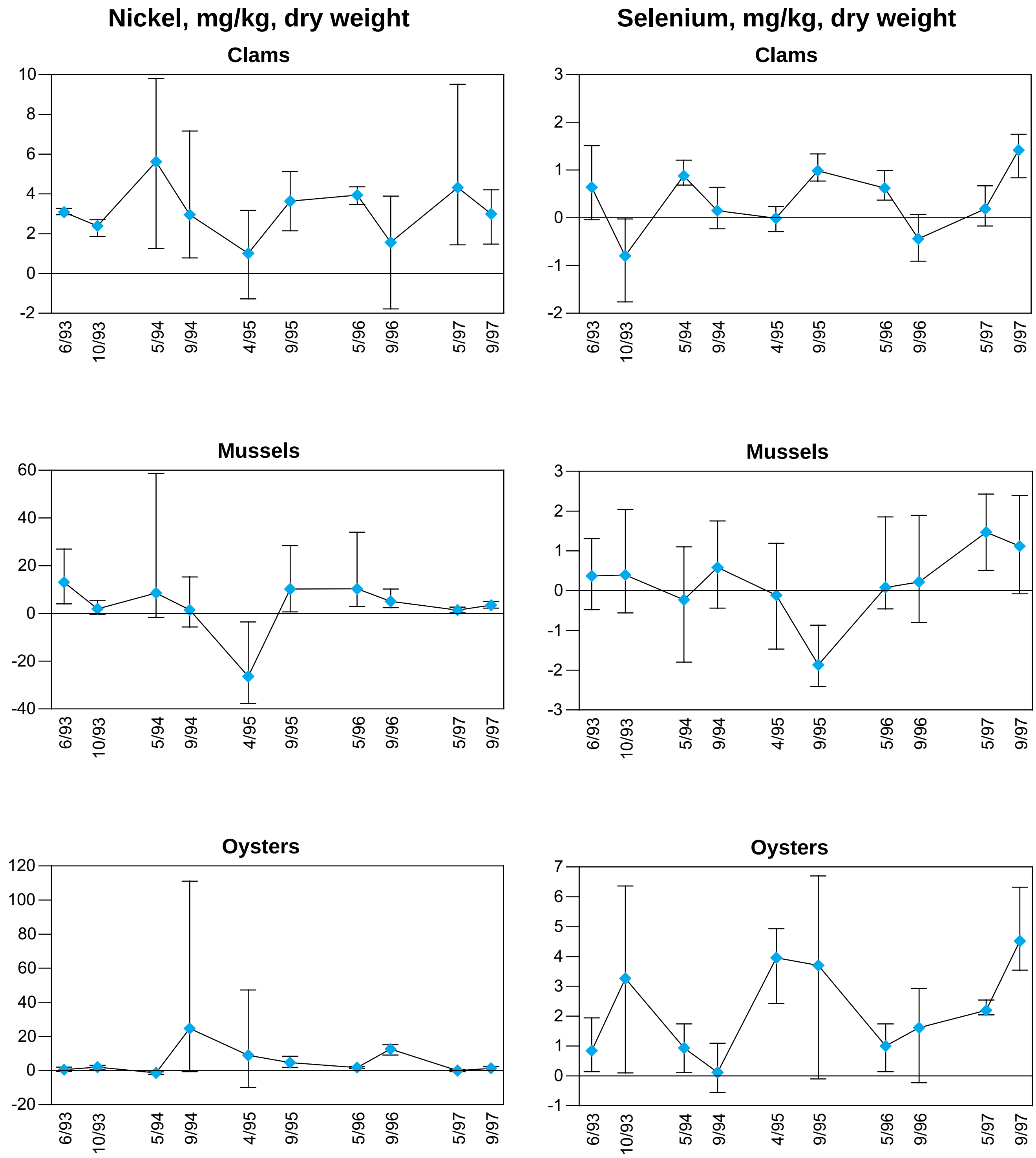

Figure 5.19 (continued). Trace element accumulation or depuration in parts per million dry weight (ppm) in three transplanted bivalve species for ten sampling periods from 1993–1997. Note different y-axis scales.

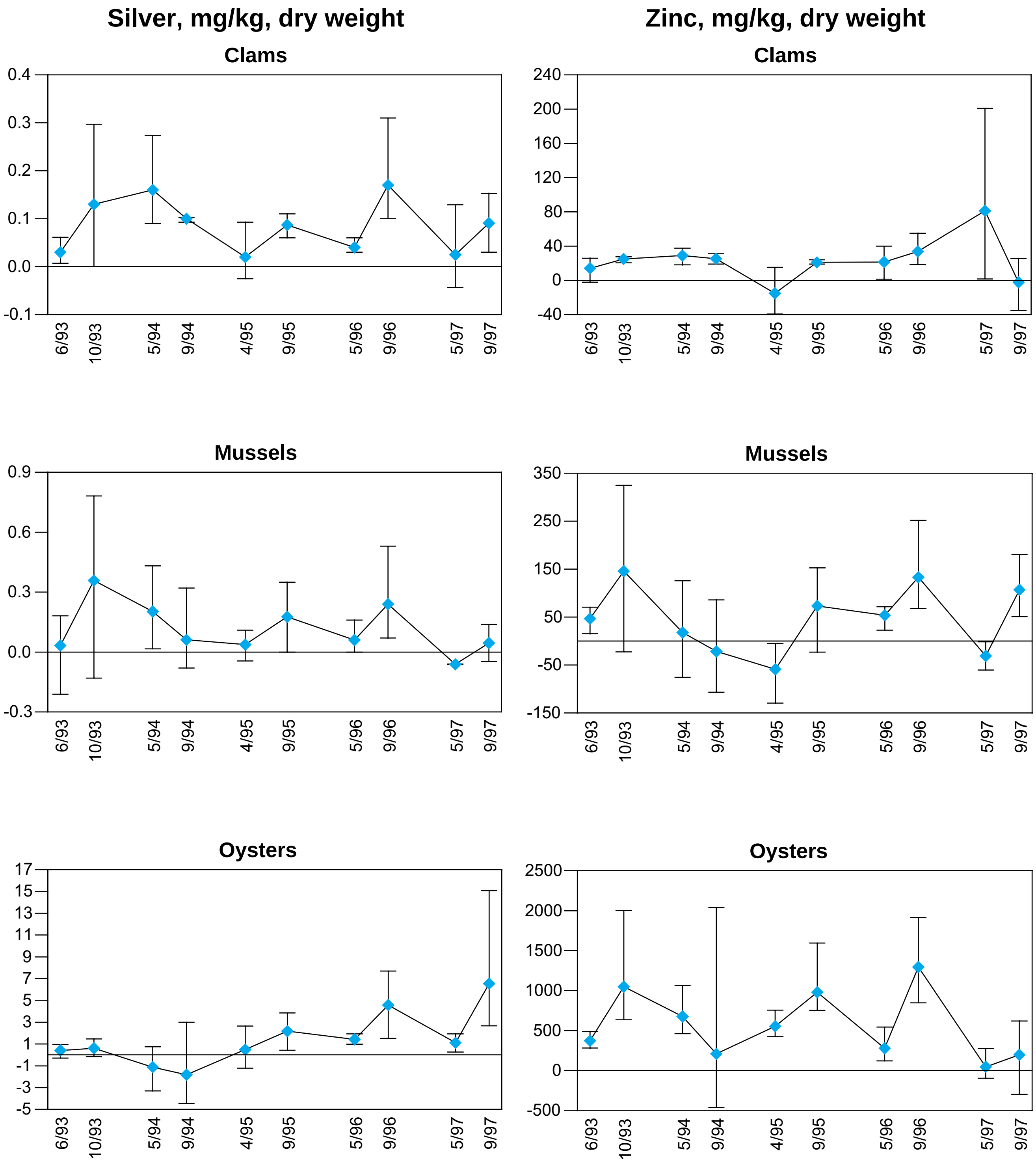

Figure 5.19 (continued). Trace element accumulation or depuration in parts per million dry weight (ppm) in three transplanted bivalve species for ten sampling periods from 1993–1997. Note different y-axis scales.

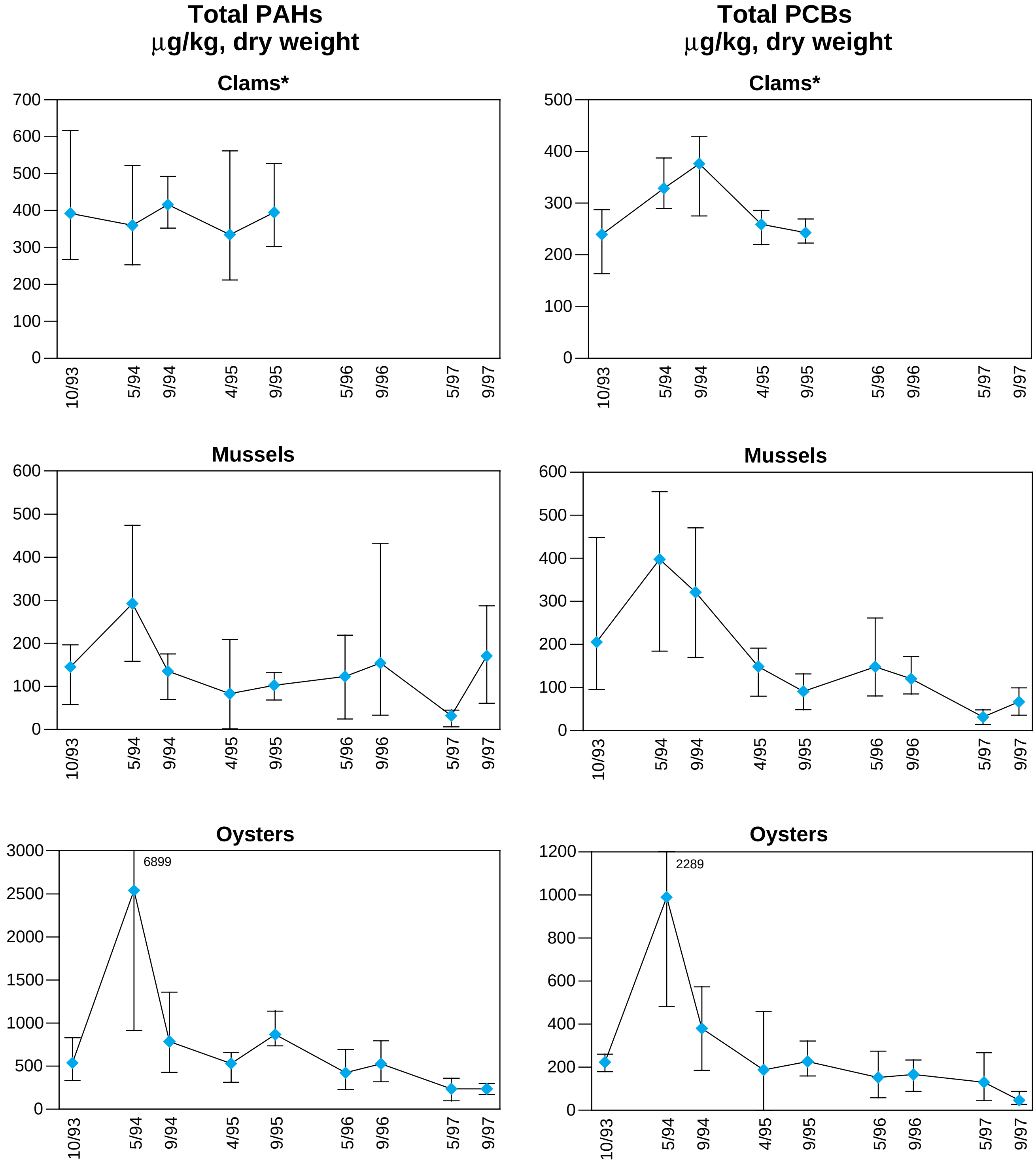

Figure 5.20. Trace organic accumulation or depuration in parts per billion dry weight (ppb) in three species of transplanted bivalves for nine sampling periods from 1993–1997 (mean of all stations). Accumulation or depuration was calculated by subtracting initial tissue (T-0) concentrations from concentrations after deployment. Bars indicate range of values within a sampling period. * In 1996, the reference population of “clean” *Corbicula fluminea* at Lake Isabella crashed and disappeared. Despite exploring several other potential reference sites, field staff was unable to find sufficiently large populations suitable for transplantation into the Estuary. Beginning with the 1996 data, *C. fluminea* bioaccumulation could no longer be compared with previous years due to the initial high concentrations of some contaminants, particularly trace organics, which biases bioaccumulation estimates toward the low end. Note different y-axis scales.

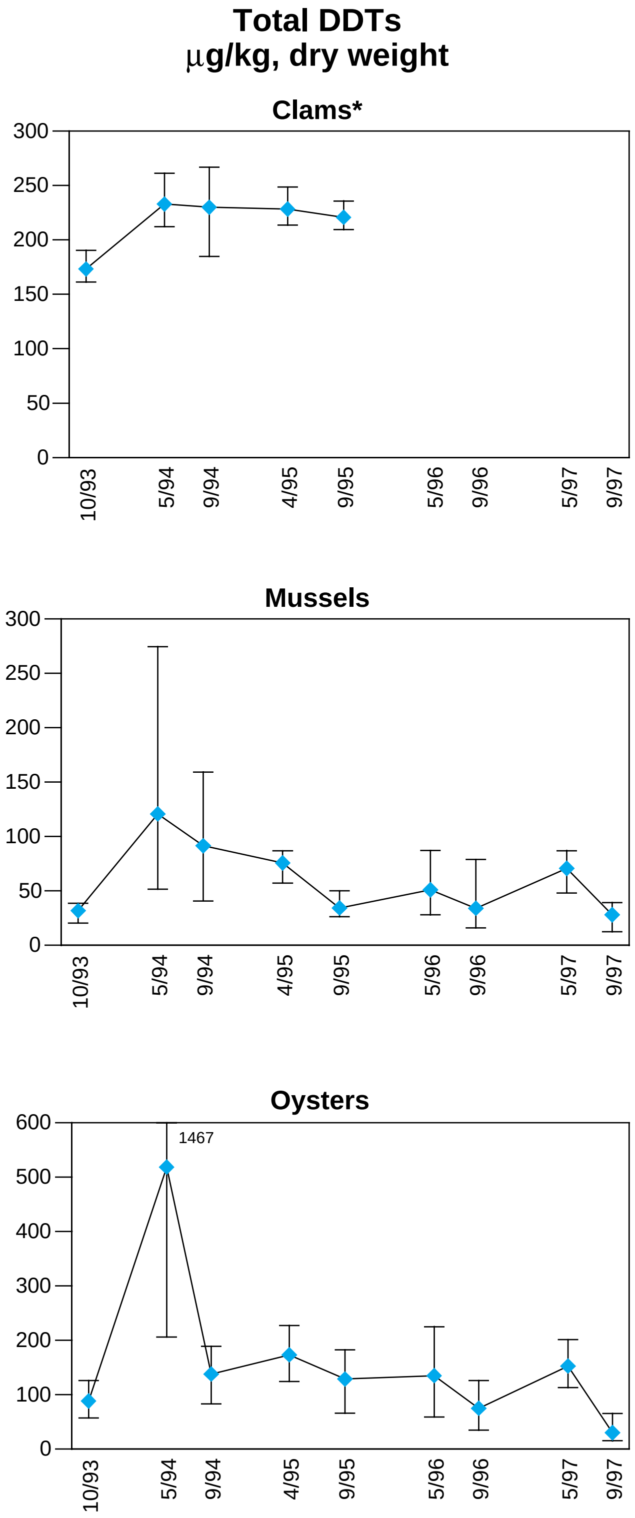

Figure 5.20 (continued). Trace organic accumulation or depuration in parts per billion dry weight (ppb) in three species of transplanted bivalves for nine sampling periods from 1993–1997 (mean of all stations). Note different y-axis scales.

A Review of Monitoring with Bivalves: Charting a Course for the Future

Dane Hardin, Applied Marine Sciences
Rainer Hoenicke and Michael May, San Francisco Estuary Institute

Introduction

Following five years of RMP bioaccumulation monitoring, we determined that a more in-depth analysis of the database might enable us to assess how well this monitoring component met its original goals, and how it might evolve in the next few years to meet the new RMP objectives and help answer relevant management questions (see *Chapter 2: Review Implementation*). The purpose of this article is to continue synthesis of the growing bioaccumulation database in order to stimulate discussion for design improvements, including those related to monitoring contaminant effects (a new RMP objective). In 1998, the Steering Committee decided to modify the monitoring objectives to include a description of general sources and loadings of contamination to the Estuary and measurements of contaminant effects on selected parts of the Estuary ecosystem.

The initial goals of the RMP bivalve monitoring component were to:

1. Measure the bioavailable portion of contaminants in the water column.
2. Evaluate which contaminants may be transferred to higher trophic levels of the food web, and thus to what extent certain contaminants may pose health risks to wildlife and humans.

These general goals implicitly address the overall original RMP objectives of determining seasonal and long-term trends in chemical and biological water quality. Unlike the “snapshot” in time of contamination obtained from water sampling three times each year, the bioaccumulation component provides an integrative measure of water contamination, since exposure to varying concentrations during the three-month deployment is reflected in their tissues. Also, measuring dissolved and total/near-total contaminant concentrations in water and sediment alone does not reveal how likely it is for various contaminants to enter the food web and pose risks to higher-order consumers. Bivalves are very good trend indicators for many contaminants, particularly lipophilic compounds such as chlorinated hydrocarbons and PAHs, because their contaminant body burdens equilibrate with corresponding contaminants in the surrounding environment relatively quickly (Russell and Gobas, 1989; Stephenson, 1992). However, not all contaminants are bioaccumulated in the same way by bivalves, and bivalve species differ in their bioaccumulation characteristics. Overall, oysters accumulate trace metals to a greater degree than mussels and clams, while mussels accumulate PCBs to higher concentrations than oysters and clams. We have also learned that bivalves are unsuitable indicators for mercury bioaccumulation, although we know that methylmercury is highly accumulative in other species and is rapidly magnified in the food web, as evidenced in fish tissue levels that are of human health concern (see *Chapter 6: Pilot and Special Studies*). Similarly, bivalves do not appear to bioaccumulate arsenic and are likely of limited use in determining bioavailability of this contaminant, for trend monitoring, or as a diagnostic tool for identifying potential problem areas.

Time series of raw trace substance concentrations in bivalves (not normalized for tissue lipid content) for the last ten sampling events starting in 1993 (with the exception of *Corbicula fluminea*) are depicted in Figures 5.19 and 5.20 in *Bivalve Monitoring Trends*. As with water and sediment concentration *trends*, numerous environmental variables influence bivalve concentrations. In most cases, the raw data essentially show no trends, and the *noise* surrounding the *signal* of interest (tissue concentrations over time) is so large that any changes over time or spatial patterns require many years of measurements before any definitive conclusions can be drawn.

Gunther *et al.* (in press) and Gunther and Davis (1997) analyzed bivalve data by combining the databases of the RMP and the State Mussel Watch Program, thus increasing the size of the data set. They found statistically significant declines in silver in both Central and South Bay reaches, and less pronounced declines in mercury and lead concentrations. They also demonstrated that lipid normalization of chlorinated hydrocarbon concentrations in bivalves reveals patterns that otherwise may not be apparent. The combined databases normalized to tissue lipid content show dramatic initial declines in concentrations of chlorinated hydrocarbons, such as PCBs and DDTs after use restrictions were implemented. When 1997 data are added to the trend lines at Coyote Creek (BA10), Yerba Buena Island (BC10), and San Pablo Bay (BD20), unnormalized bivalve PCB concentrations show consistent declines at all stations between 1994 and 1997, but lipid-normalized PCB concentrations indicate a decline only at Yerba Buena Island (Figure 5.21). We have expanded this type of analysis to explore how water quality parameters, such as temperature, salinity, dissolved oxygen, suspended sediment, and chlorophyll *a* concentrations, might affect tissue concentrations and bivalve condition.

Bivalves as Tools for Meeting New RMP Objectives

As part of designing the RMP so it can answer the management questions formulated in 1998 (see *Chapter 2: Review Implementation*), we examined the possible role of biomonitoring with bivalves in meeting the new RMP objectives and answering some of the management questions. Bivalve measurements can serve more purposes than this RMP element was originally designed for. They have the potential or have been shown to contribute to the following assessments:

1. Bivalve tissue concentrations are probably the most suitable indicator *for long-term trends* of many contaminants in the Estuary.
2. Bivalves are suitable as a *diagnostic tool* for problem identification and prioritization of follow-up action, and for the identification of most bioaccumulative substances.
3. Studies by the U.S. Geological Survey and others (Luoma and Linville, 1996; Salazar and Salazar, 1995, 1998) have shown the potential of bivalves as *indicators of pollutant effects*.
4. Bivalve tissue concentrations can represent a “substitute” or *enhancement of water measurements*, since they integrate water concentrations over long periods of time.
5. They represent a tool to *estimate contaminant transfer to higher trophic levels* to be used by others for ecosystem risk assessments.
6. Bivalves can serve as a tool for prioritizing problem watersheds or sites that may contribute contaminants of concern to the Estuary (*pollutant source/pathway indicator*).

If the potential of bivalves in meeting these goals is to be recognized and evaluated for incorporation into the new RMP design, the kinds of analyses summarized in this article are a necessary first step.

Data Analysis

The analyses described in this article proceeded in three phases. First, we determined what quantitative relationships exist between bivalve data (i.e., trace substance concentrations and indicators of bivalve health) and key environmental factors. These quantitative relationships were then used to statistically adjust the bivalve data to remove the suggested effects of these environmental factors. This enabled us to determine the magnitude of the noise surrounding the signal that the environmental factors are likely to contribute. Second, we examined in more detail whether there were statistically significant spatial and temporal

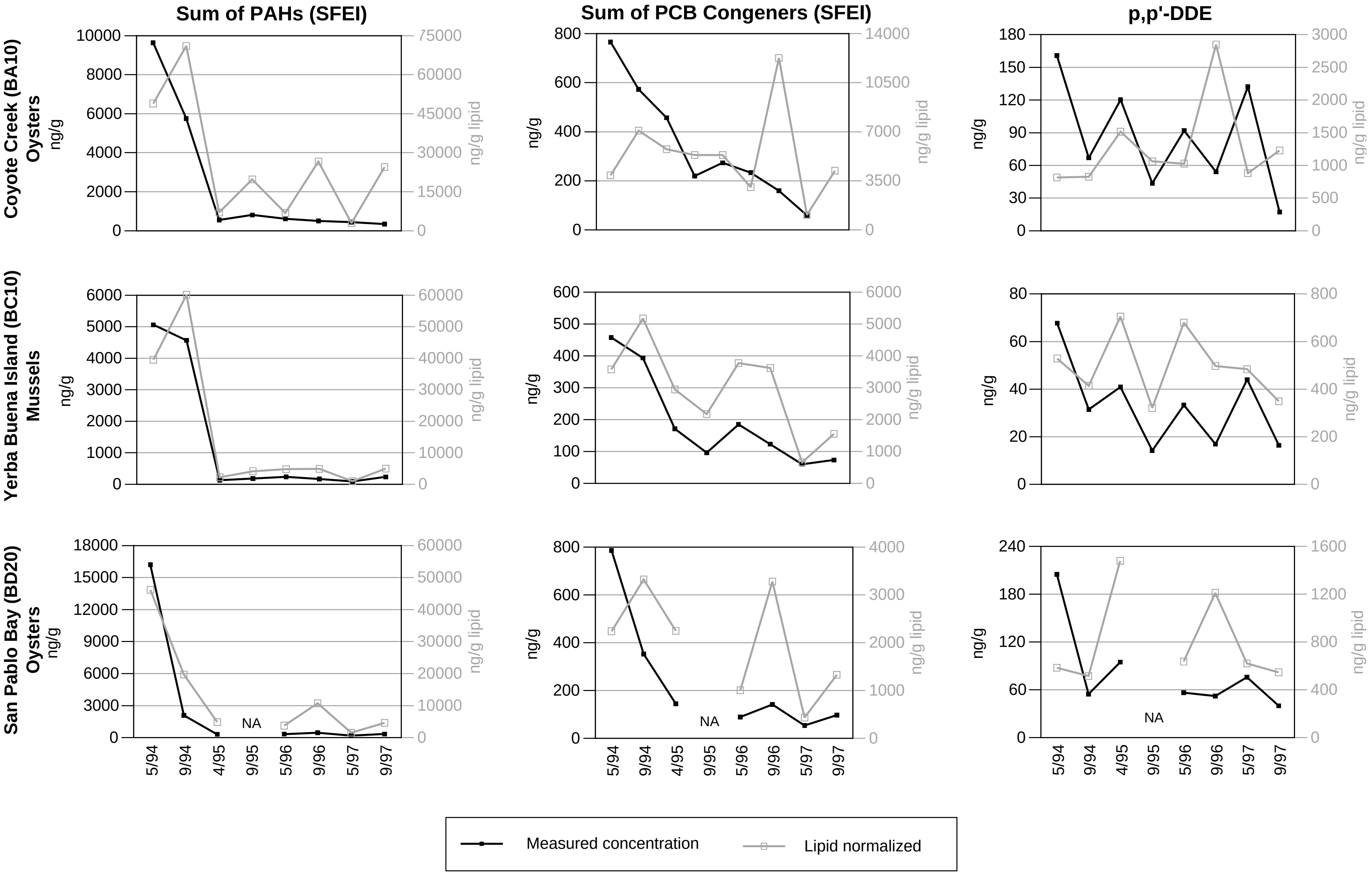

Figure 5.21. Trace organic trends at three RMP Base Program stations. Please note differences in y-axes within graphs. NA = not analyzed.

trends where the same species was deployed and whether these trends were affected by adjusting the bivalve data for the suggested effects of the environmental factors. This analysis was performed to determine whether there were significant trends and whether the trends were more or less apparent after the data had been adjusted. Third, we compared bivalve concentrations of trace substances, with and without adjustment for the suggested effects of environmental factors, with water concentrations in the particulate and dissolved fractions. The purpose of this analysis was to demonstrate the value that bivalve measurements add to the RMP, and to determine whether adjustment of bivalve data improved this value.

The initial step was to determine whether bivalve measurements may be affected by natural water quality parameters in ways that confound our ability to describe spatial and temporal trends in bioavailable contaminants. The influence of various water quality parameters on invertebrate bioaccumulation has been demonstrated in numerous studies (Absil *et al*., 1994; Hutchins *et al*., 1996; Luoma and Bryan, 1982; Magni, 1993; Wang *et al*., 1995; Wright and Zamuda, 1987). Although the bivalve bioaccumulation method has been used worldwide to determine spatial and temporal variation in contaminants, RMP data and other studies have shown that the San Francisco Estuary provides unique challenges because of the very high spatial and temporal variation in natural water quality parameters.

Statistical analyses were performed to determine whether chlorophyll, dissolved oxygen, salinity, temperature, and total suspended solids might be affecting the bivalves and their accumulation of trace substances. U.S. Geological Survey (USGS) water quality data, collected as part of the RMP base program and supported by both RMP and Department of Interior funds, are recorded on approximately monthly intervals (http://sfbay.wr.usgs.gov/access/wqdata/archive). We obtained these data for stations near seven RMP bivalve sites (Figure 5.22). The USGS data from the three 1-m intervals that bracketed our bivalve deployment depths were averaged across all the USGS cruises that occurred during each bivalve deployment period to estimate the conditions experienced by the bivalves for that site and deployment.

The potential effects of water quality parameters on bivalves were examined for four indicators of bivalve health (condition, tissue growth, percent tissue lipid, and survival) and the tissue concentrations of trace metals and selected organic contaminants (totals for PAHs, PCBs, DDTs, chlordanes, and HCHs). It should be noted that, based on initial analysis by Gunther and Davis (1997), all trace organic contaminants were normalized to lipid concentrations prior to these analyses. Oysters (*Crassostrea gigas*) were examined at Coyote Creek and Davis Point; mussels (*Mytilus californianus*) were examined at Redwood Creek, Alameda, Red Rock, and Pinole Point; and clams (*Corbicula fluminea*) were examined at Sacramento River (Figure 5.22).

The statistical procedures involved backward stepwise regressions using the water quality parameters as independent variables and the bivalve parameters as dependent variables. These procedures enable determination of which independent variables account for most of the variation in each dependent variable. The backward stepwise procedure initially begins with all of the independent variables included in the analysis, and the variables that account for the least variation are successively removed at each step until the remaining independent variable(s) account for most of the remaining variation in the dependent variable. The resulting regression coefficient approximates the percentage of the variation in the dependent variable that is due to the independent variables. The probability (P) indicates whether the resulting regression line for the relationship between the independent and dependent variables is statistically significantly different from zero (i.e., $P < 0.05$ is significantly different from zero). Because data were occasionally missing for some water quality parameters, whenever the stepwise procedures found a slope significantly different from zero, multiple regression was performed using only the important independent variables. The residuals from the multiple regressions (i.e., the distance of each data

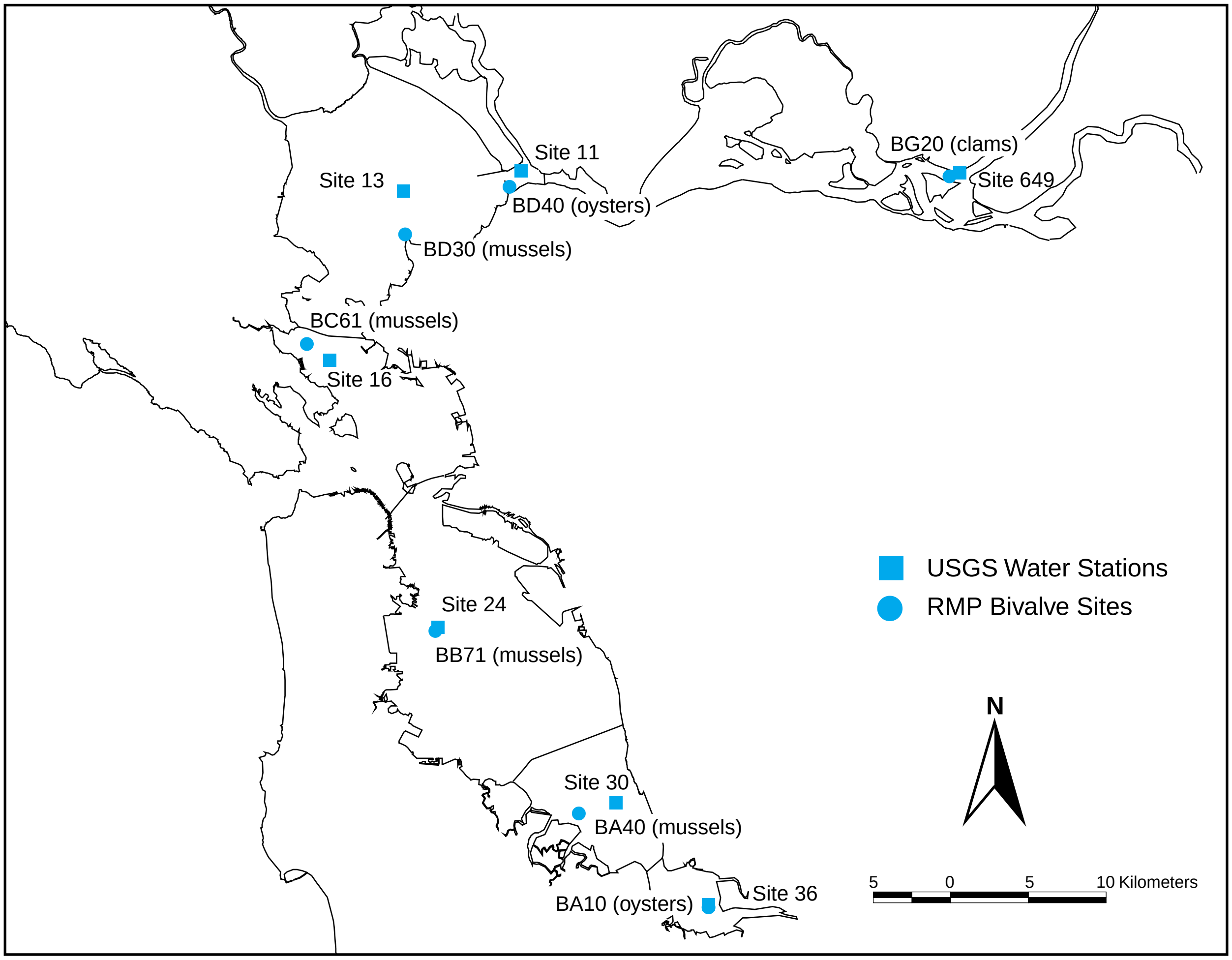

Figure 5.22. Site map of water quality and tissue monitoring sites.

point from the regression line) were used to correct the dependent variables (i.e., bivalve data) for the effects of the water quality parameters using the method of Hebert and Keenleyside (1995).

Following the application of any appropriate corrections to the bivalve measurements, we examined in more detail bivalve concentrations of copper, mercury, PAHs, and determined whether spatial and temporal trends were statistically significant. These four trace substances were selected because of their regulatory importance. Regressions of bivalve contaminant concentrations against time were tested to determine whether temporal trends were significant and whether trends differed among sites. Analyses of variance (ANOVA) were performed for the aggregate of all sites within each bivalve species to determine whether overall differences among years were significant. ANOVA was also performed to determine whether sites with the same species differed.

Caution must be used when interpreting the results of the regression analyses. Regression analyses assume the independent variables (i.e., chlorophyll, dissolved oxygen, salinity, temperature, total suspended solids, and time) affect the dependent variables (i.e., bivalve health and trace substance concentrations). While we have used the regression analyses to establish whether there are systematic relationships or correlations between the independent and dependent variables, true cause and effect relationships can only be confirmed through experimentation. Regression analyses were more advantageous for our purposes than calculations of simple correlations because the resulting regression equations provide the means to adjust the bivalve data for the suggested effects of environmental factors.

Effects of Water Quality Parameters on Bioaccumulation

Numerous bivalve measurements are significantly related to chlorophyll, dissolved oxygen, salinity, temperature, and total suspended solids (Tables 1, 2, and 3 in *Appendix E*). Thirteen out of 18 bivalve measurements were significantly related to these water quality parameters for *Mytilus californianus* (Table 1 in *Appendix E*), 11 out of 18 were significantly related for *Crassostrea gigas* (Table 2 in *Appendix E*), and five out of 18 were significantly related for *Corbicula fluminea* (Table 3 in *Appendix E*). This finding in and of itself is not surprising and was expected.

Mussels

Health and Survival

Condition, tissue growth, percent lipid, and survival of *M. californianus* were all significantly positively related to various combinations of chlorophyll, dissolved oxygen, and salinity. The suggested effects of dissolved oxygen on condition, tissue growth, and percent lipid are consistent with the super-saturated dissolved oxygen concentrations prevalent in the surf zone where these bivalves naturally live. The sharp decline in survival below salinities of 18–20 parts per thousand (Figure 5.23) was fit best with a second-order polynomial regression. This relationship between survival and salinity is also consistent with the open coast habitat of this species.

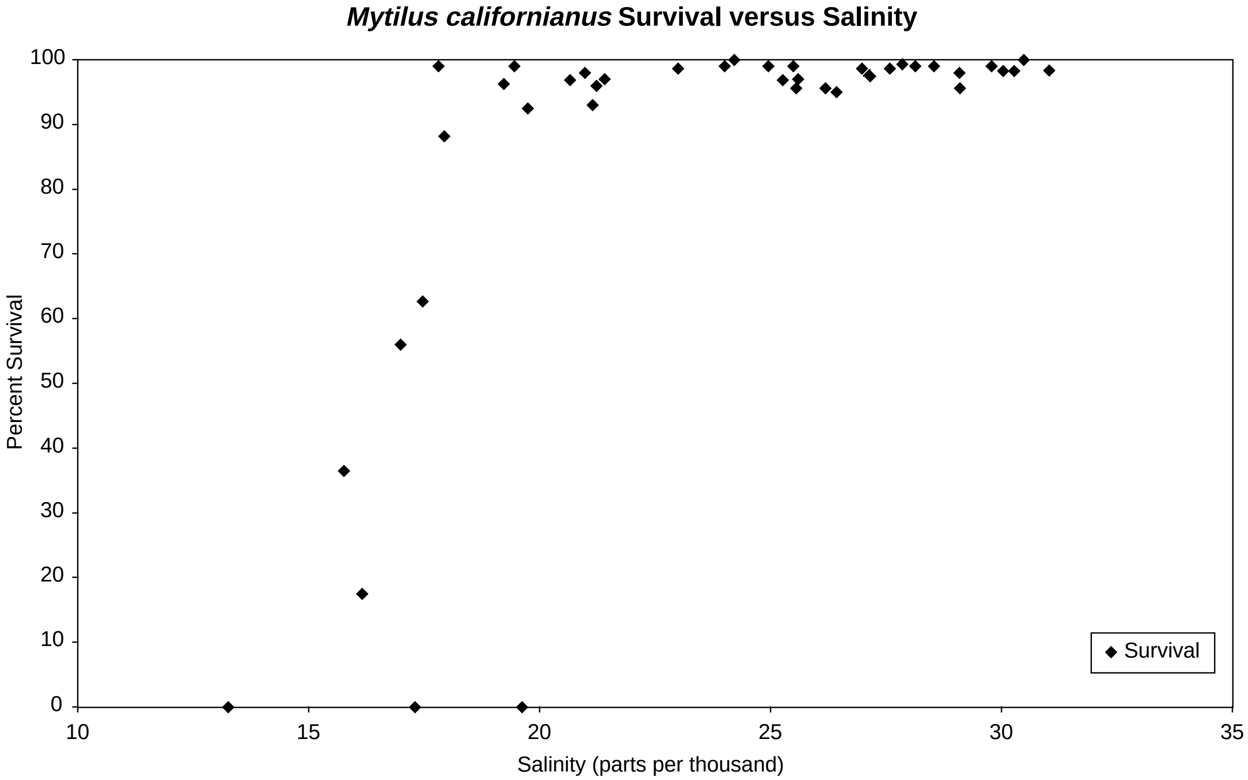

Figure 5.23. Survival in mussels versus salinity. Data are from 1993 to 1997.

Bioaccumulation

All the water quality parameters, either singly or in combination, were significantly related to bioaccumulation of silver, cadmium, lead, nickel, zinc, PAHs, PCBs, chlordanes, and HCHs. Only chlorophyll and temperature were consistent regarding the direction of their effects, with bioaccumulation of cadmium and zinc being negatively related to chlorophyll, and bioaccumulation of silver, lead, and zinc being positively related to temperature.

Oysters

Health and Survival

Condition and tissue growth were negatively related to temperature, with the negative relationship between survival and temperature also being nearly significant. Percent lipid was positively related to dissolved oxygen, salinity, and total suspended solids.

Bioaccumulation

All the water quality parameters, either singly or in combination, also were significantly related to bioaccumulation in oysters. Only dissolved oxygen and temperature were consistent in the direction of their suggested effects, with bioaccumulation of cadmium, PAHs, and PCBs being negatively related to dissolved oxygen, and bioaccumulation of chromium and lead being positively related to temperature.

Clams

Health and Survival

Condition and survival were negatively related to temperature and chlorophyll, respectively, while condition was positively related to salinity.

Bioaccumulation

Only three contaminants, silver, PCBs, and HCHs, were significantly related to water quality parameters, probably because of the low sample size related to using data from a single site. All three contaminants were negatively related to chlorophyll. Silver and HCHs were also negatively related to total suspended solids and temperature, respectively.

These findings confirm the common wisdom that water quality variables influence bivalve parameters, although this is the first time that RMP data were subjected to this kind of analysis. It is now possible to determine whether the adjustments to bivalve data for the suggested effects of water quality variables reveal spatial or temporal trends that are not apparent using unadjusted data. These analyses also reveal that some water quality parameters in the Estuary are outside optimum levels for the bivalves and may thus affect bioaccumulation. For example, dissolved oxygen concentrations in the Estuary seem to affect the “health” (as defined by tissue growth, condition, and percent lipid) of *Mytilus californianus*. This species also survived poorly where salinities averaged less than 20‰. Summer temperatures in the Estuary also may exceed those that are optimal for *Crassostrea gigas*. This is not to say that these bivalves are inappropriate for bioaccumulation monitoring in the Estuary, but that the ultimate data users need to be clear regarding the limitations of these indicators and the uncertainties surrounding the data. Although these transplanted bivalves experience environmental stress in the Estuary, resident bivalves may also experience stress at certain times of the year. Nevertheless, drawing conclusions about the absolute biomagnification potential of a trace substance based solely on transplanted bivalves may not be appropriate, and other bivalve species that are better adapted to Estuary conditions may be more suitable for contaminant transfer estimates.

Spatial and Temporal Trends and the Effects of Analyzing Adjusted Bivalve Data

Numerous spatial and temporal trends occurred for copper, mercury, PAHs, and PCBs in the three species of bivalves. If significant regressions were not found between tissue contaminant concentrations and the natural variables (Tables 1, 2, and 3 in *Appendix E*), trends are described for unadjusted data (i.e., measured concentrations of metals and lipid-normalized concentrations of organic contaminants). But, whenever possible, data are used that have been adjusted for the suggested effects of the natural variables.

Mussels

ANOVA results indicated relatively little spatial variation in the bioaccumulation of copper, mercury, PAHs, and PCBs (Table 5.1). Only PCBs indicated a significant difference (Table 5.1), with mussels deployed at Redwood Creek bioaccumulating greater amounts of PCBs than did mussels deployed at Pinole Point or Red Rock. This is in agreement with previous conclusions drawn from sediment and water data comparing Estuary reaches, with the South Bay exhibiting higher PCB concentrations than the Central Bay reach.

ANOVA results also indicated relatively little temporal variation in the bioaccumulation of copper, mercury, PAHs, and PCBs (Table 5.1). Tissue concentrations of copper were significantly greater in 1996 and 1997 than in 1993 and 1994, suggesting increases through time. Unadjusted PCBs were significantly lower in 1995 and 1997 than in 1994. There were no significant differences among years for mercury or PAHs.

Regression analyses using unadjusted data revealed that significant temporal trends were site-specific (Figures 5.24–5.27). The increase of copper through time was significant at Pinole Point and nearly significant at Redwood Creek, but not at Alameda or Red Rock. The very slight decline in mercury through time was nearly significant at Alameda, but not at any other site. Increases in PAH concentrations were nearly significant at Red Rock and Redwood Creek, but not at Alameda or Pinole Point. Decreases in PCB concentrations were nearly significant at Alameda and Redwood Creek, but the decreases at Red Rock and Pinole Point were much less pronounced and insignificant.

Adjustment of tissue concentrations of PAHs and PCBs for suggested effects of environmental variables provided contrasting results (Figures 5.28 and 5.29). In the case of PAHs, adjustment of

Table 5.1. ANOVAs for differences among sites and years in concentrations of four contaminants in mussels.

Contaminant	P	*a posteriori* results[a]
Among Sites		
Copper[b]	.8983	Red Rock Pinole Point Alameda Redwood Creek
Mercury[b]	.6059	Pinole Point Redwood Creek Red Rock Alameda
PAH[b]	.8769	Red Rock Alameda Redwood Creek Pinole Point
PAH[c]	.7814	Pinole Point Alameda Red Rock Redwood Creek
PCB[b]	.0531	Redwood Creek Alameda Red Rock Pinole Point
PCB[c]	.0348	Redwood Creek Alameda Pinole Point Red Rock
Among Years		
Copper[b]	.0011	1996 1997 1995 1994 1993
Mercury[b]	.1262	1994 1995 1993 1997 1996
PAH[b]	.0725	1997 1996 1995 1994
PAH[c]	.0693	1997 1996 1994 1995
PCB[b]	.0295	1994 1996 1995 1997
PCB[c]	.0213	1994 1995 1996 1997

[a] Sites and years are arranged with the highest mean on the left and the lowest mean on the right. Sites or years that are connected by a common line are not significantly different.

[b] Unadjusted data were tested.

[c] Adjusted data were tested.

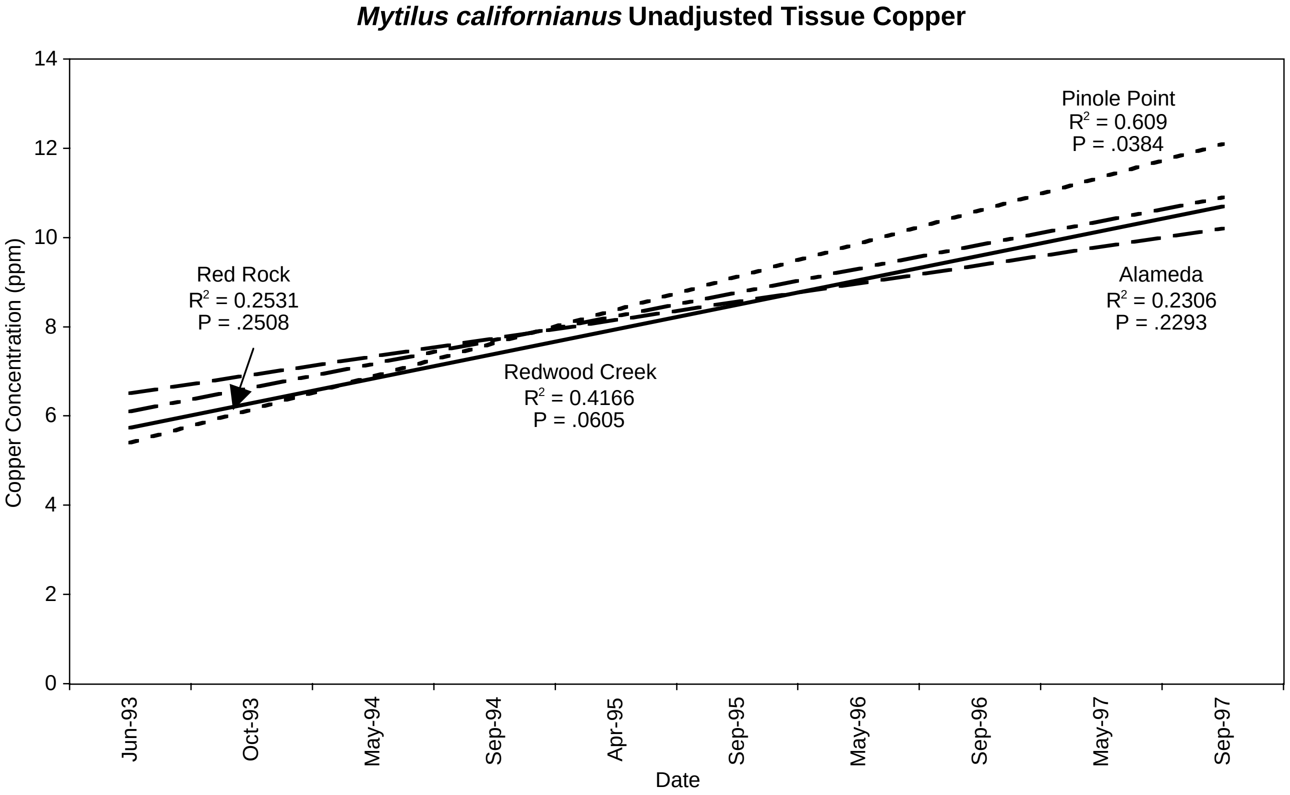

Figure 5.24. Trendlines for unadjusted copper in mussels at four sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

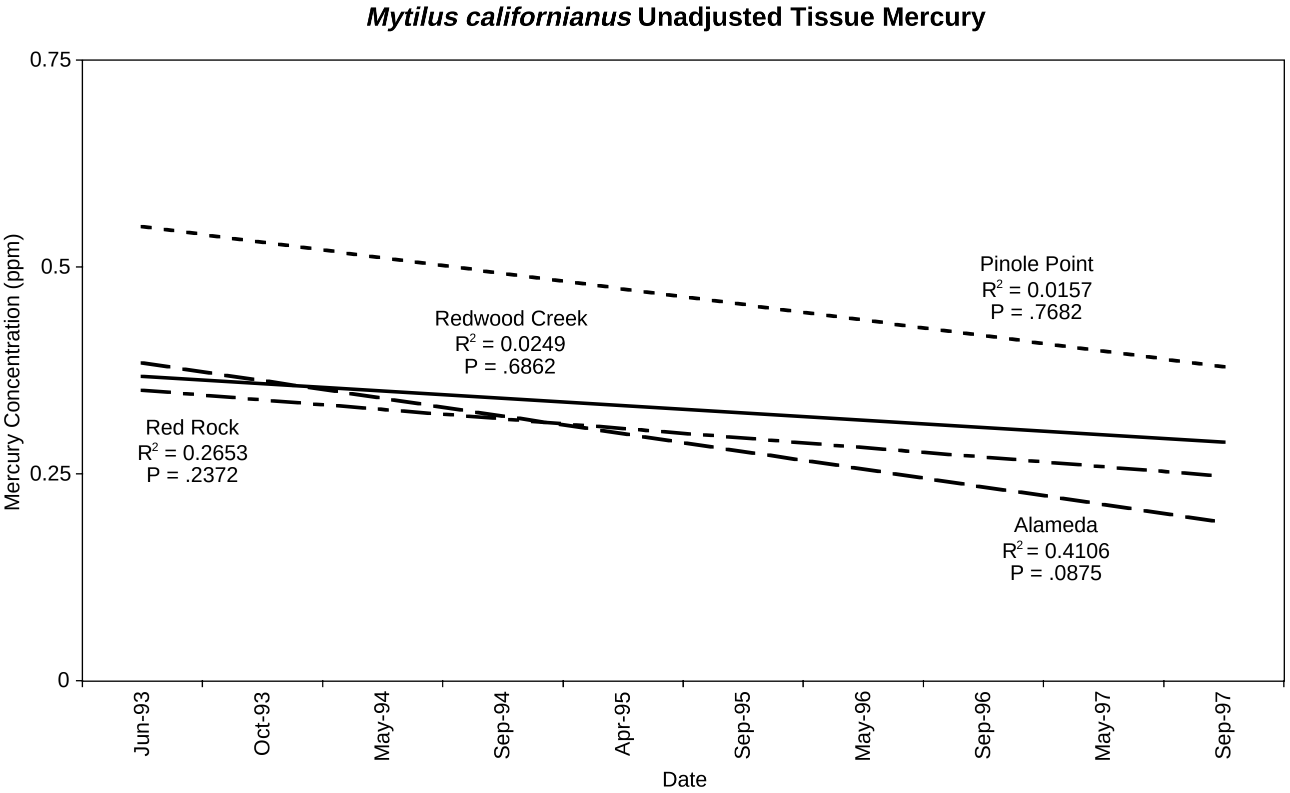

Figure 5.25. Trendlines for unadjusted mercury in mussels at four sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

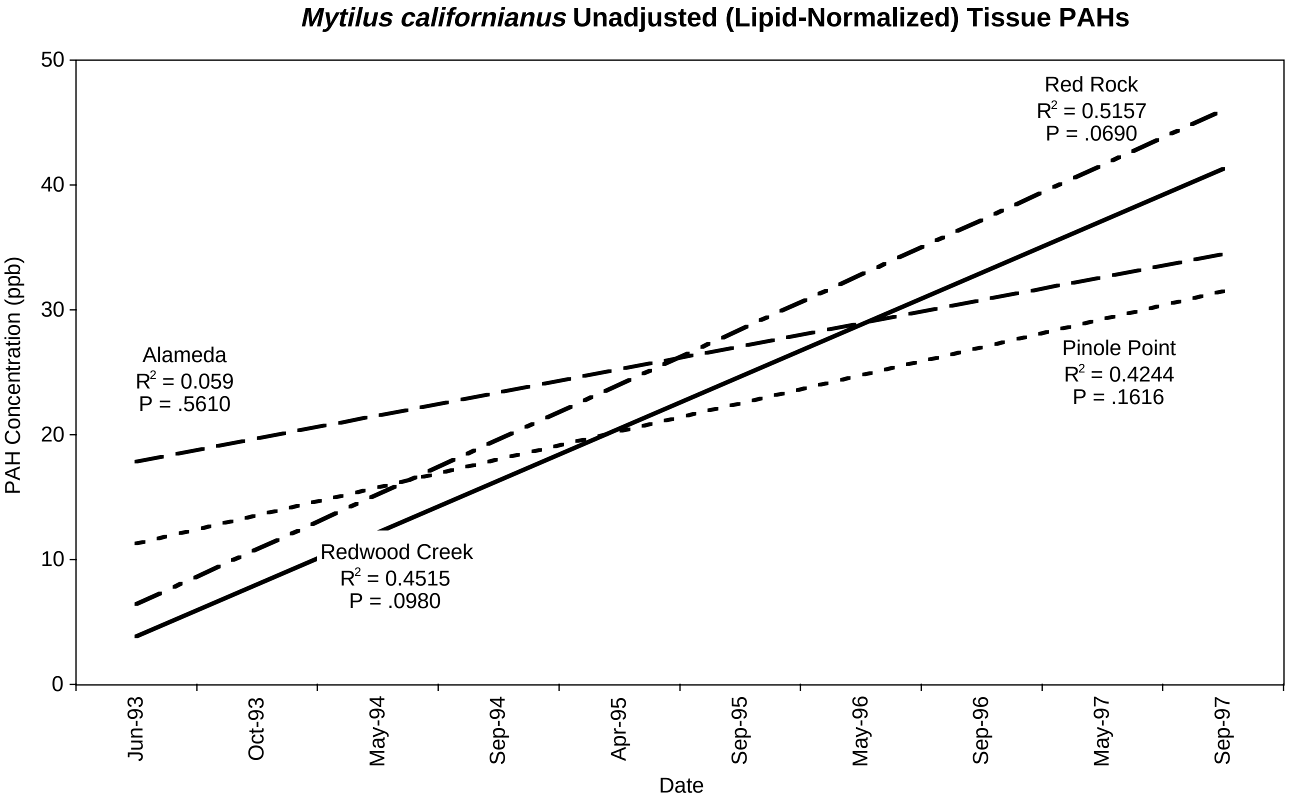

Figure 5.26. Trendlines for unadjusted (lipid-normalized) PAHs in mussels at four sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

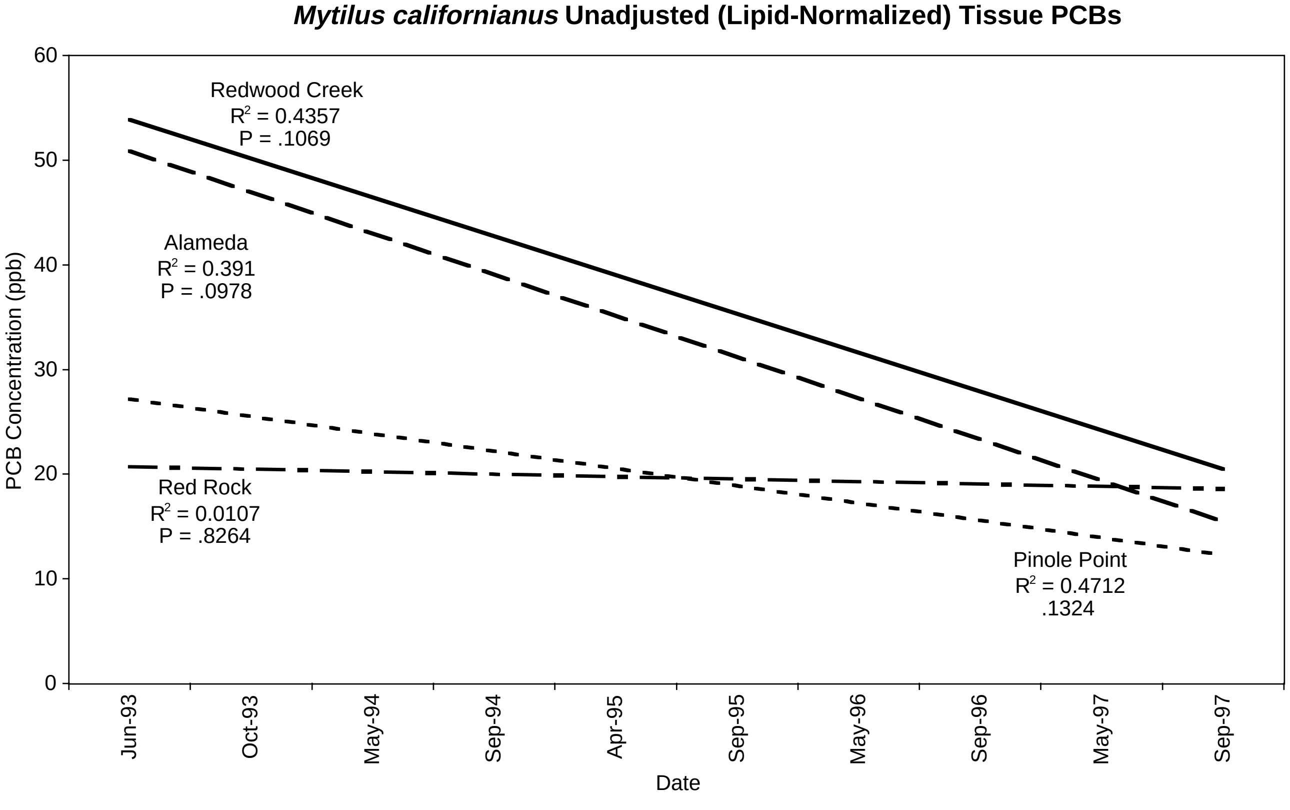

Figure 5.27. Trendlines for unadjusted (lipid-normalized) PCBs in mussels at four sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

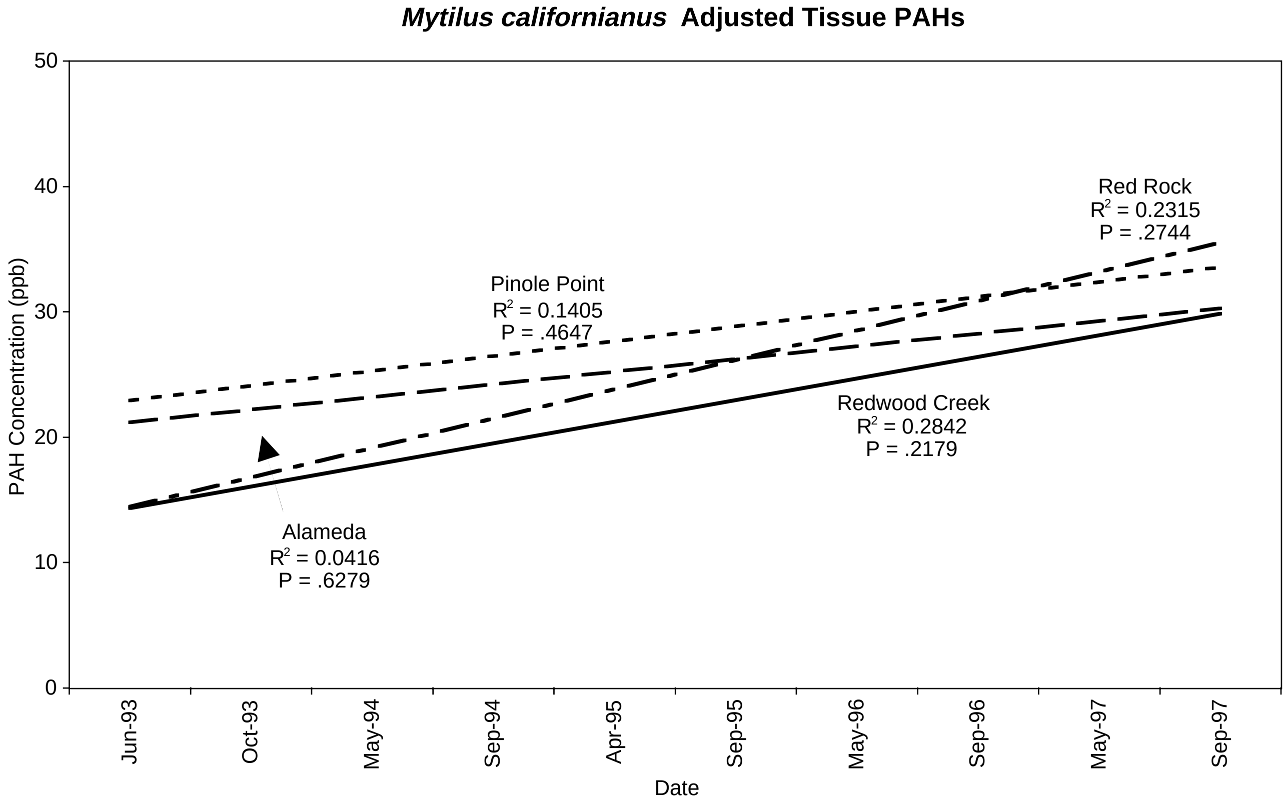

Figure 5.28. Trendlines for adjusted PAHs in mussels at four sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

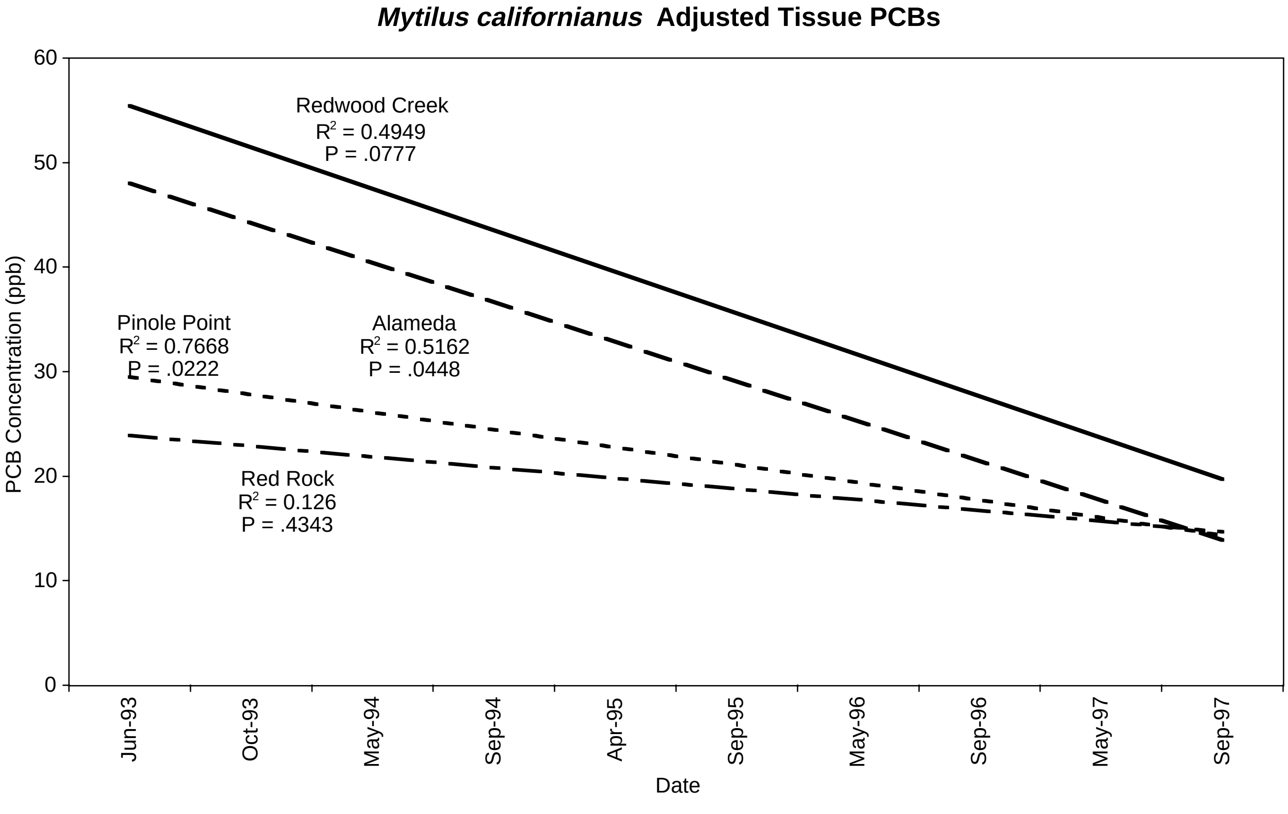

Figure 5.29. Trendlines for adjusted PCBs in mussels at four sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

tissue data made no difference in the ANOVA results, except that with unadjusted data, 1994 had the lowest mean, and with adjusted data, 1995 had the lowest mean (Table 5.1). Probabilities were also lower with adjusted data indicating reduced variation within sites and years. Use of adjusted data in the analysis of temporal trends indicated much less dramatic increases through time at each site than were seen with the unadjusted data (Figure 5.26), suggesting that the increases seen in the unadjusted data may be related to differences in dissolved oxygen and total suspended solids. P values for trend lines based on adjusted data were substantially greater, indicating that by adjusting PAH tissue concentrations, any hint of increases through time was even less pronounced than for unadjusted data (Figures 5.26 and 5.28; Table 5.2). In the case of PCBs, adjustment of tissue data made no difference in the ANOVA test for differences among sites, although the probabilities were lower (Table 5.1). The ANOVA test for differences among years gave different results for adjusted and unadjusted data, with adjusted data suggesting more consistent decreases from year to year. Use of adjusted PCB data in the analysis of temporal trends suggested decreases through time that were more significant than for unadjusted data (Figures 5.27 and 5.29; Table 5.2).

Oysters

Unlike for mussels, ANOVAs for oysters revealed no significant differences among sites or years for any of the four contaminants (Table 5.3). Unadjusted tissue data also revealed no significant trends through time (Figures 5.30–5.33).

Adjustment of oyster tissue data changed the slope of some trend lines, but all remained insignificantly different from zero (Figures 5.34–5.37). For instance, the insignificant decrease in copper at Coyote Creek for unadjusted data became an insignificant increase with adjusted data (Figures 5.30 and 5.34; Table 5.2) and the insignificant

Table 5.2. Comparison of temporal trends using adjusted and unadjusted bivalve data. Direction of arrow indicates increases or decreases from 1993 to 1997. * = probability that slope of trendline was different from zero was < 0.2. ** = probability that slope of trendline was different from zero was < 0.1. *** = probability that slope of trendline was different from zero was < 0.05. NA = not analyzed.

Trace Substance					
Site/Species	**Treatment**	**Copper**	**Mercury**	**PAH**	**PCB**
Coyote Creek/Oysters	Adjusted	↓	↑	↑ *	↓
	Unadjusted	↑	↑	↑	↓
Redwood Creek/Mussels	Adjusted	NA	NA	↑	↓ **
	Unadjusted	↑ **	↓	↑ **	↓ *
Alameda/Mussels	Adjusted	NA	NA	↑	↓***
	Unadjusted	↑	↓ **	↑	↓ **
Red Rock/Mussels	Adjusted	NA	NA	↑	↓
	Unadjusted	↑	↓	↑ **	↓
Pinole Point/Mussels	Adjusted	NA	NA	↑	↓***
	Unadjusted	↑ ***	↓	↑ *	↓ *
Davis Point/Oysters	Adjusted	↓	↓	↓	↓ **
	Unadjusted	↓	↓	↑	↓ *
Sacramento River/Clams	Adjusted	NA	NA	NA	↓
	Unadjusted	↑ ***	↑ **	↑	↓***

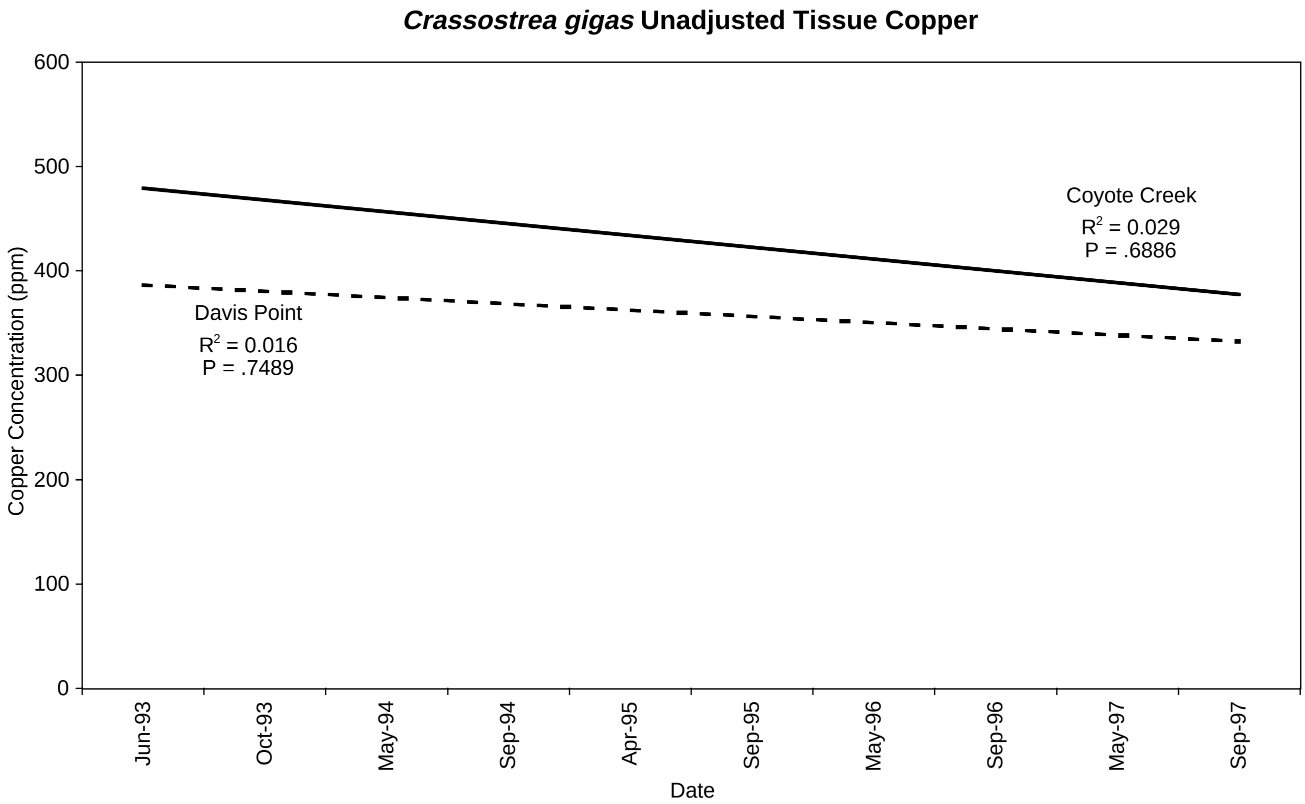

Figure 5.30. Trendlines for unadjusted copper in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

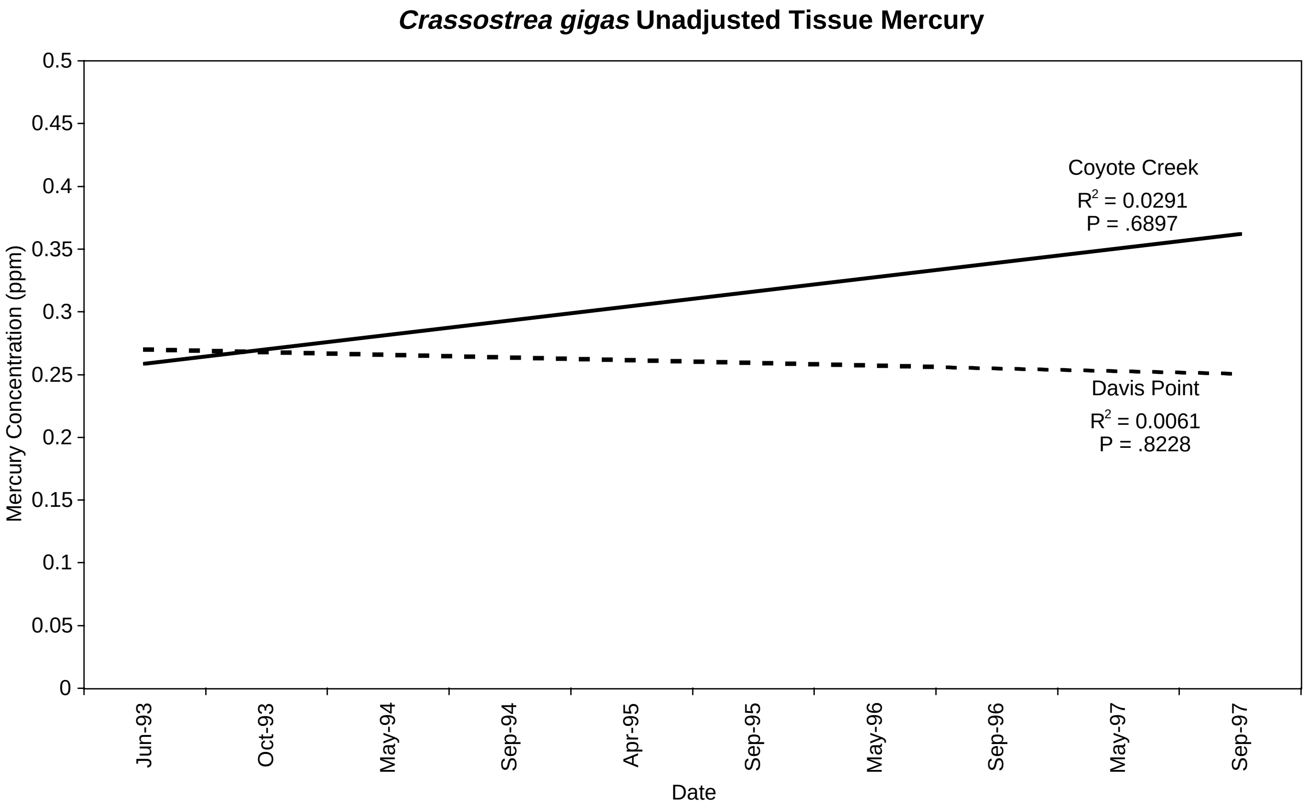

Figure 5.31. Trendlines for unadjusted mercury in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

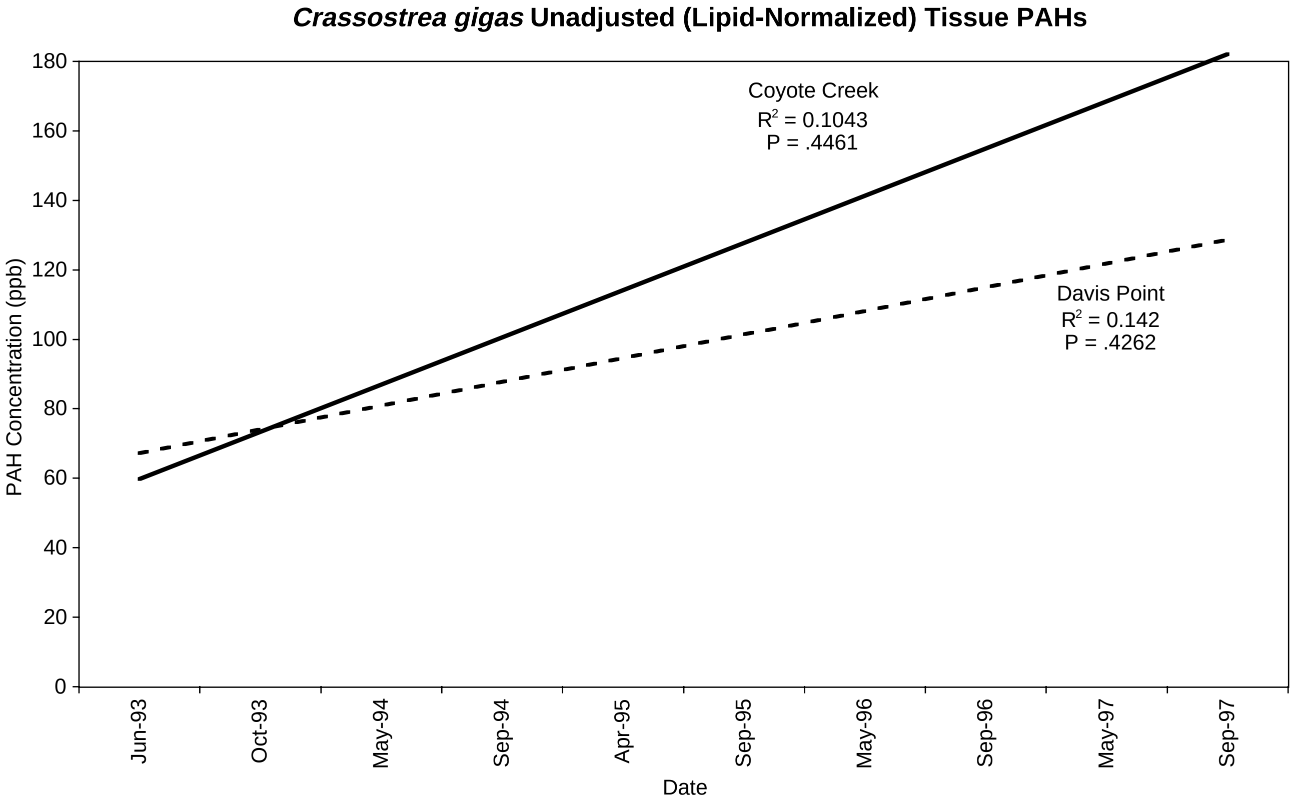

Figure 5.32. Trendlines for unadjusted (lipid-normalized) PAHs in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

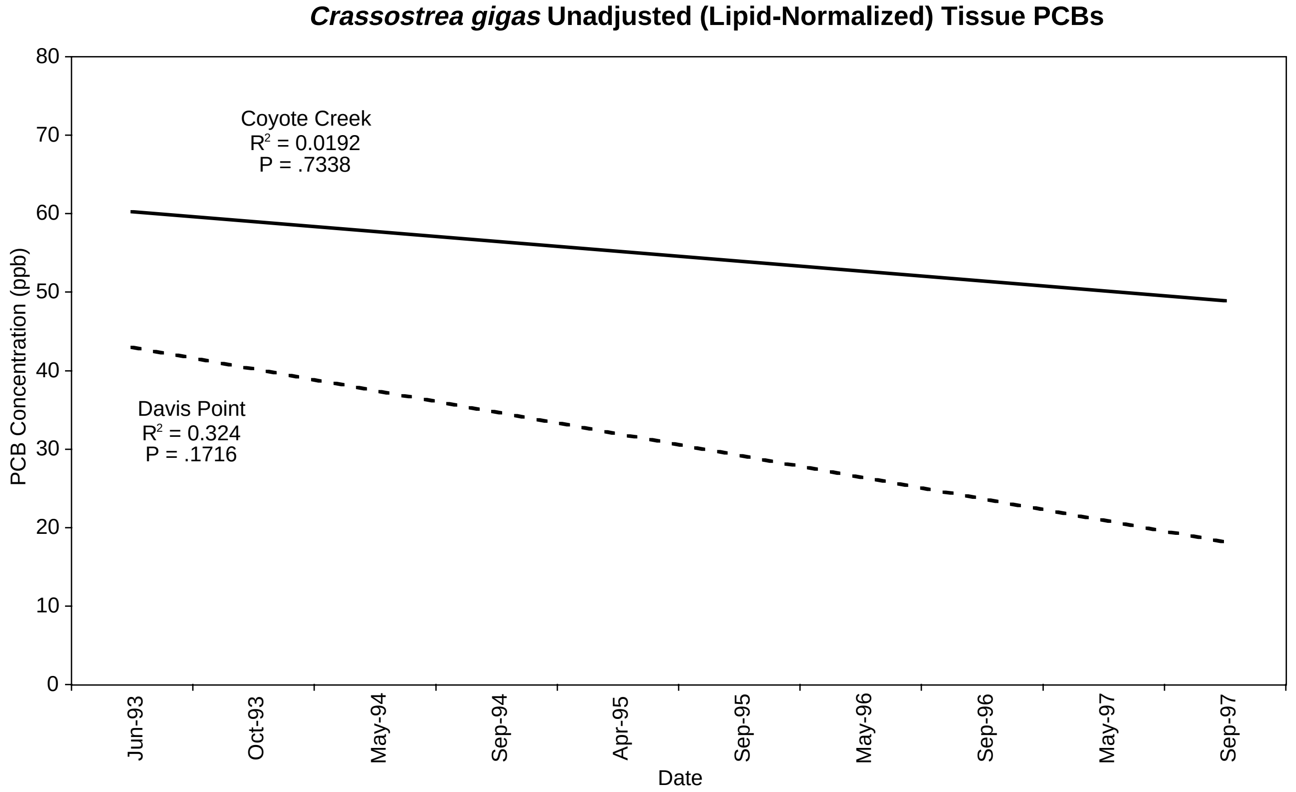

Figure 5.33. Trendlines for unadjusted (lipid-normalized) PCBs in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

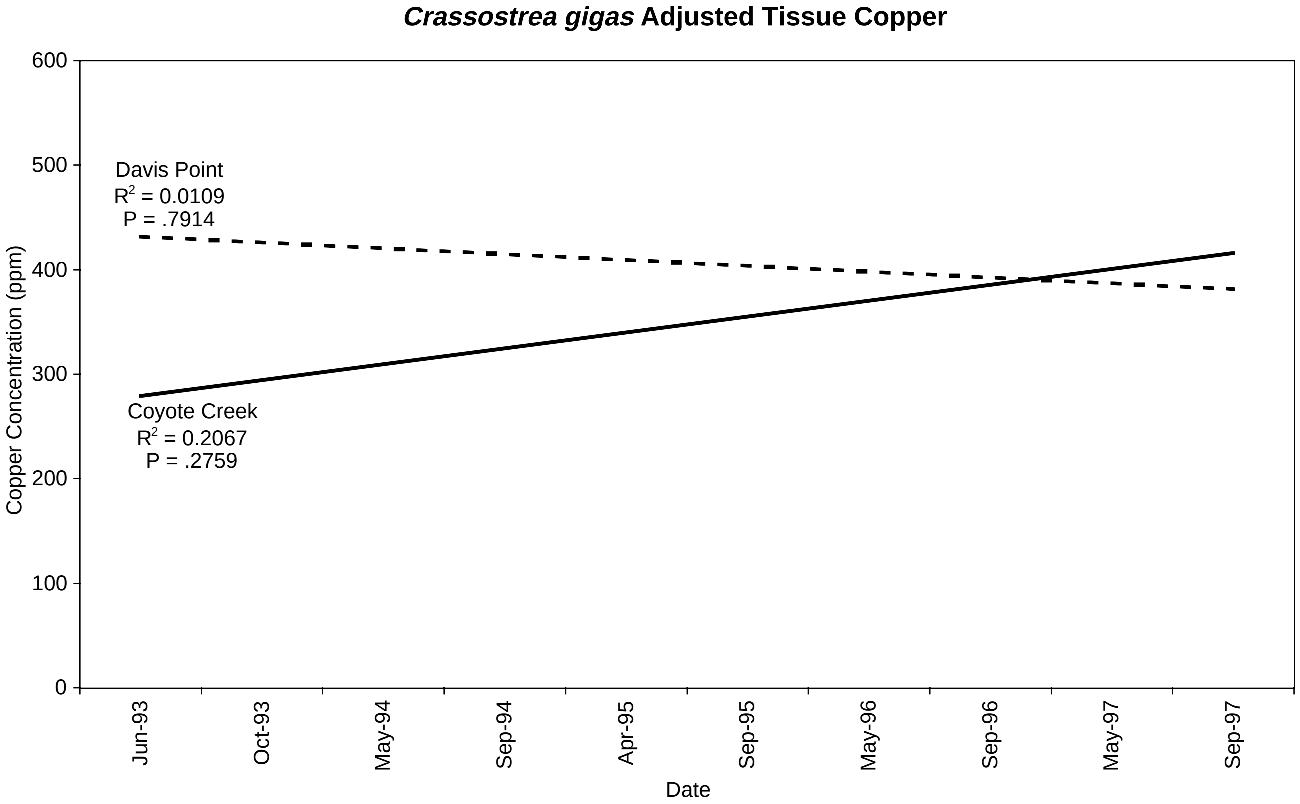

Figure 5.34. Trendlines for adjusted copper in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

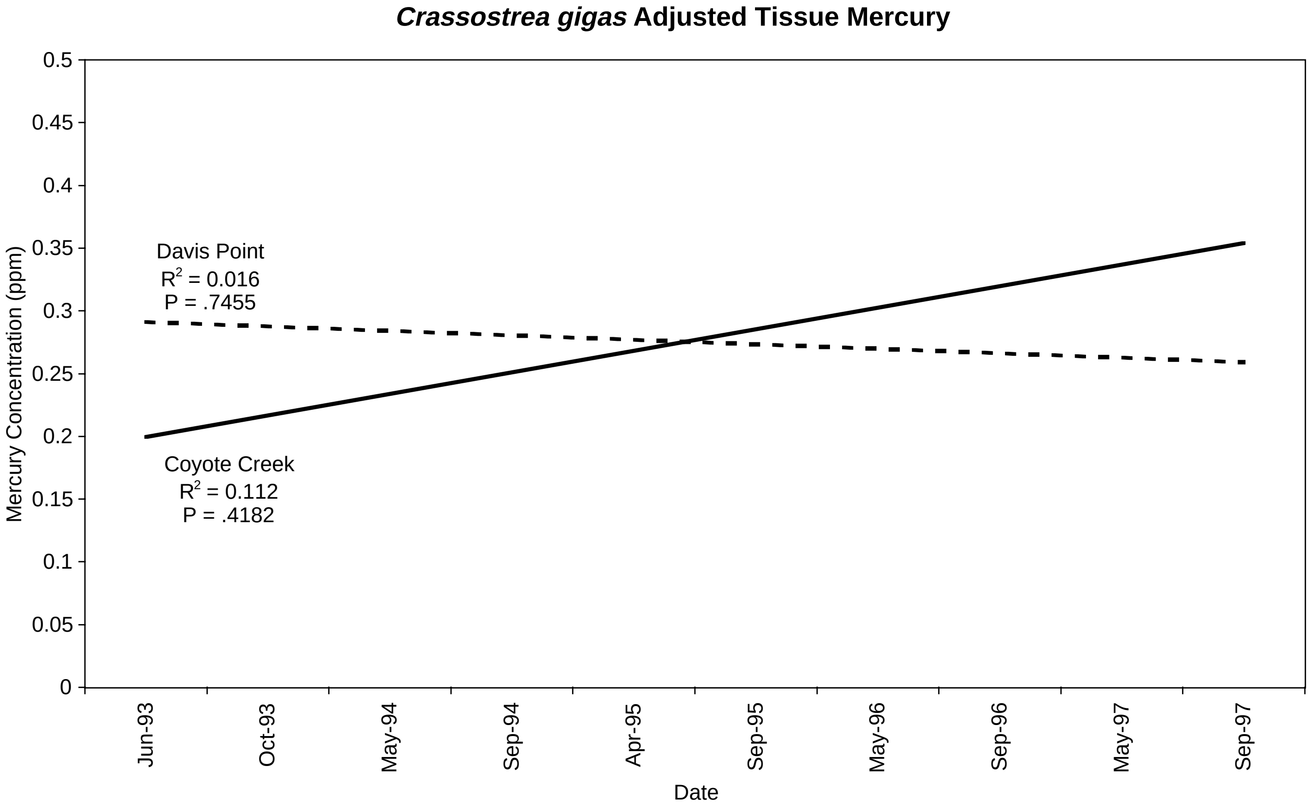

Figure 5.35. Trendlines for adjusted mercury in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

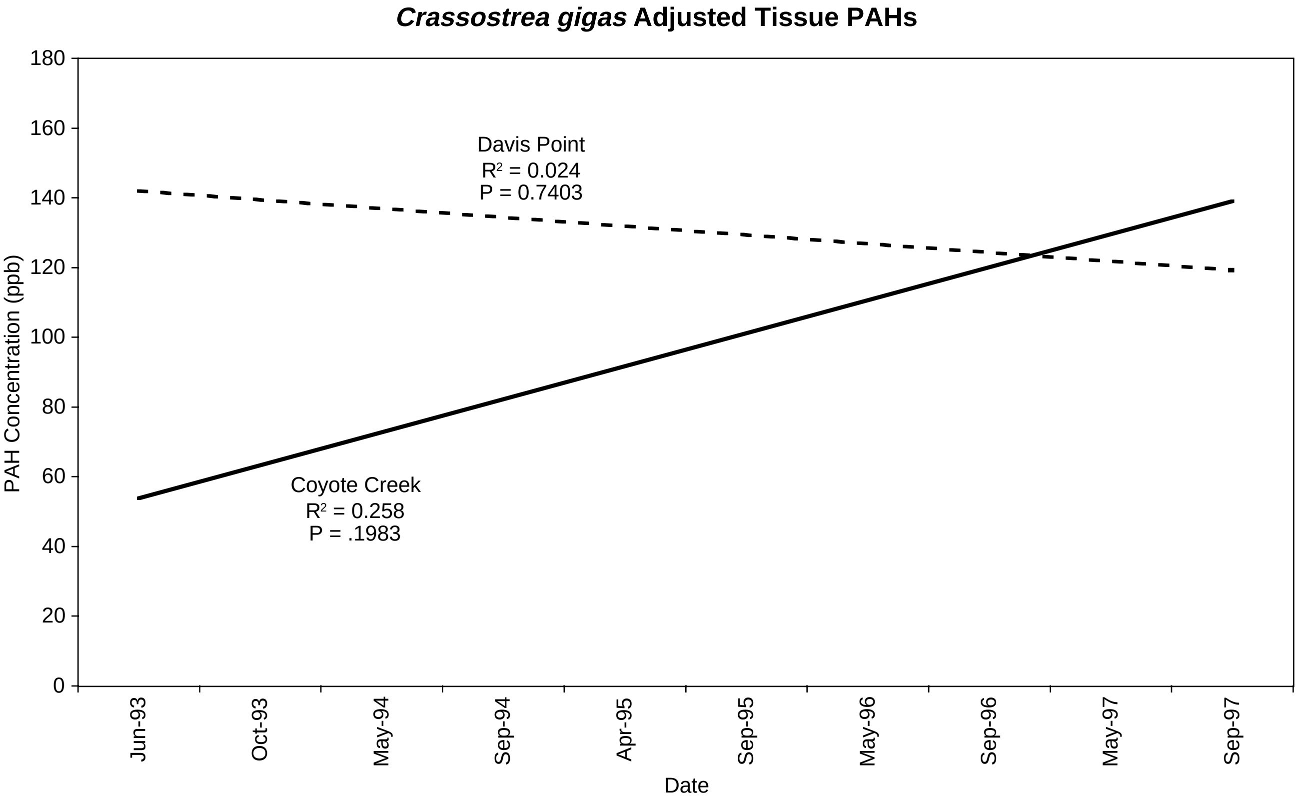

Figure 5.36. Trendlines for adjusted PAHs in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

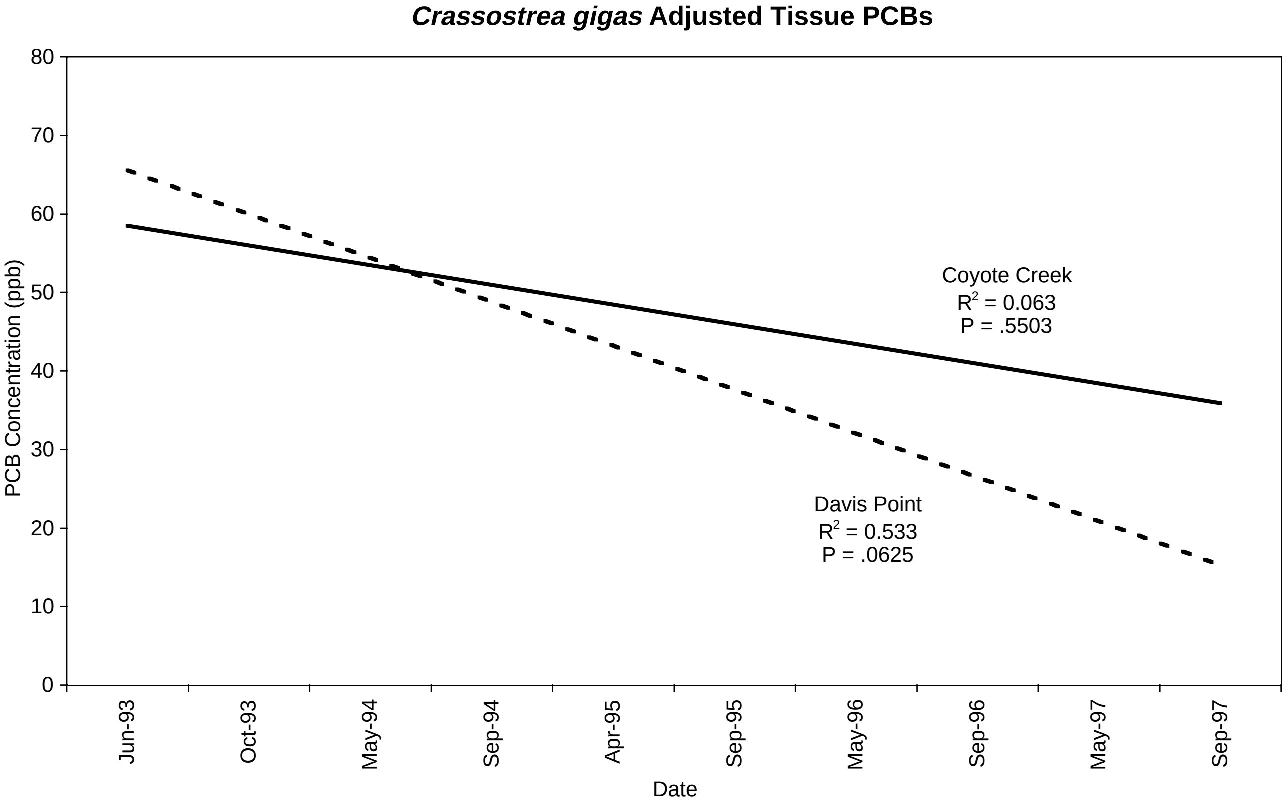

Figure 5.37. Trendlines for adjusted PCBs in oysters at two sites between June 1993 and September 1997. Regression coefficients and probabilities for trendlines are indicated.

increase in PAHs at Davis Point for unadjusted data became an insignificant decrease with adjusted data (Figures 5.32 and 5.36; Table 5.2). Use of adjusted data caused the increase and decrease in mercury at Coyote Creek and Davis Point, respectively, to become less insignificant in each case. The use of adjusted data for PCBs caused temporal trend lines to be slightly less insignificant.

Clams

Because only the Sacramento River site was used in the statistical tests for clams, it is not possible to evaluate spatial variation, although there were indications of temporal variation. Although ANOVA results revealed no significant differences among years (Table 5.4), trendlines based on unadjusted data indicated significant increases in copper, nearly significant increases in mercury, insignificant increases in PAHs, and significant decreases in PCBs (Figures 5.38–5.41). Adjustment of PCB data for the suggested effects of environmental variables made the decrease in PCBs insignificant (Figure 5.42 and Table 5.2).

We can conclude from the ANOVAs and trendlines that there are spatial and temporal differences in trace substance accumulation by bivalves in the Estuary. For example, there were higher concentrations of PCBs in mussels from South Bay sites, which are consistent with RMP water and sediment data. The decreases in PCBs at most sites, although generally not significant in unadjusted data, are also consistent with previous findings (Gunther *et al.*, in press). The increases in copper also appear to be regional because they were evident at every mussel site and the clam site. The absence of significant spatial and temporal differences in the oysters indicates that either there is a high degree of spatial variation between the oyster sites and nearby mussel sites, or the bioaccumulation trends are species-specific.

Adjustment of bivalve data for suggested effects of environmental variables often reduces variation in the data and improves our ability to detect spatial and temporal trends. In eight of the 13 cases in which ANOVAs were performed on both adjusted and unadjusted data, the adjusted

Table 5.3. ANOVAs for differences among sites and years in concentrations of four contaminants in oysters.

Contaminant	P	*a posteriori* results[a]
Among Sites		
Copper[b]	.6682	Coyote Creek Davis Point
Copper[c]	.4502	Coyote Creek Davis Point
Mercury[b]	.3633	Coyote Creek Davis Point
Mercury[c]	.7919	Coyote Creek Davis Point
PAH[b]	.3958	Coyote Creek Davis Point
PAH[c]	.2861	Davis Point Coyote Creek
PCB[b]	.0904	Coyote Creek Davis Point
PCB[c]	.5194	Coyote Creek Davis Point
Among Years		
Copper[b]	.7304	1995 1994 1996 1997
Copper[c]	.9632	1995 1994 1997 1996
Mercury[b]	.8104	1996 1997 1995 1994
Mercury[c]	.9572	1997 1994 1996 1995
PAH[b]	.7890	1996 1997 1995 1994
PAH[c]	.7053	1996 1997 1995 1994
PCB[b]	.6431	1996 1994 1995 1997
PCB[c]	.2381	1994 1996 1995 1997

[a] Sites and years are arranged with the highest mean on the left and the lowest mean on the right. Sites or years that are connected by a common line are not significantly different.
[b] Unadjusted data were tested.
[c] Adjusted data were tested.

Table 5.4. ANOVAs for differences among years in concentrations of four contaminants in clams.

Contaminant	P	a posteriori results[a]
Among Years		
Copper[b]	.2769	1997 1996 1994 1995 1993
Mercury[b]	.0881	1993 1994 1997 1995 1996
PAH[b]	.5774	1997 1994 1995
PCB[b]	.0238	1994 1996 1995 1997
PCB[c]	.5918	1996 1994 1995 1997

[a] Sites and years are arranged with the highest mean on the left and the lowest mean on the right. Sites or years that are connected by a common line are not significantly different.
[b] Unadjusted data were tested.
[c] Adjusted data were tested.

data had lower probabilities (i.e., the results were either more significant or less insignificant; Table 5.1, 5.3, and 5.4).

Analysis of bivalve data that have been adjusted for the suggested effects of environmental variables may also lead to different conclusions than would be drawn from analyzing raw, unadjusted data. For example, the slopes for copper and PAH trendlines in oysters at Coyote Creek and Davis Point, respectively, differed between adjusted and unadjusted data. Also, the greater significance of decreases in mussel PCBs and the disappearance of significance in decreases in clam PCBs after adjusting the tissue data could lead to different conclusions regarding temporal trends in trace substances in the Estuary. Such conclusions have important ramifications in the assessment of the health of the Estuary and the evaluation of regulatory requirements. Nevertheless, only in the cases of copper and PAHs at Coyote Creek and Davis Point, respectively, would conclusions about the direction of trends be affected.

Comparisons of Bivalve Bioaccumulation and Water Contaminant Concentrations

Backward stepwise regressions were performed to determine how well the concentrations of contaminants in bivalves tracked concentrations of dissolved and particulate water contaminants. More specifically, the data were analyzed to shed light on the following questions:

1. Do the data from one or two water measurements during a bivalve deployment account for significant variation in the bivalve data? In other words, are high or low water concentrations reflected by corresponding bivalve tissue concentrations?

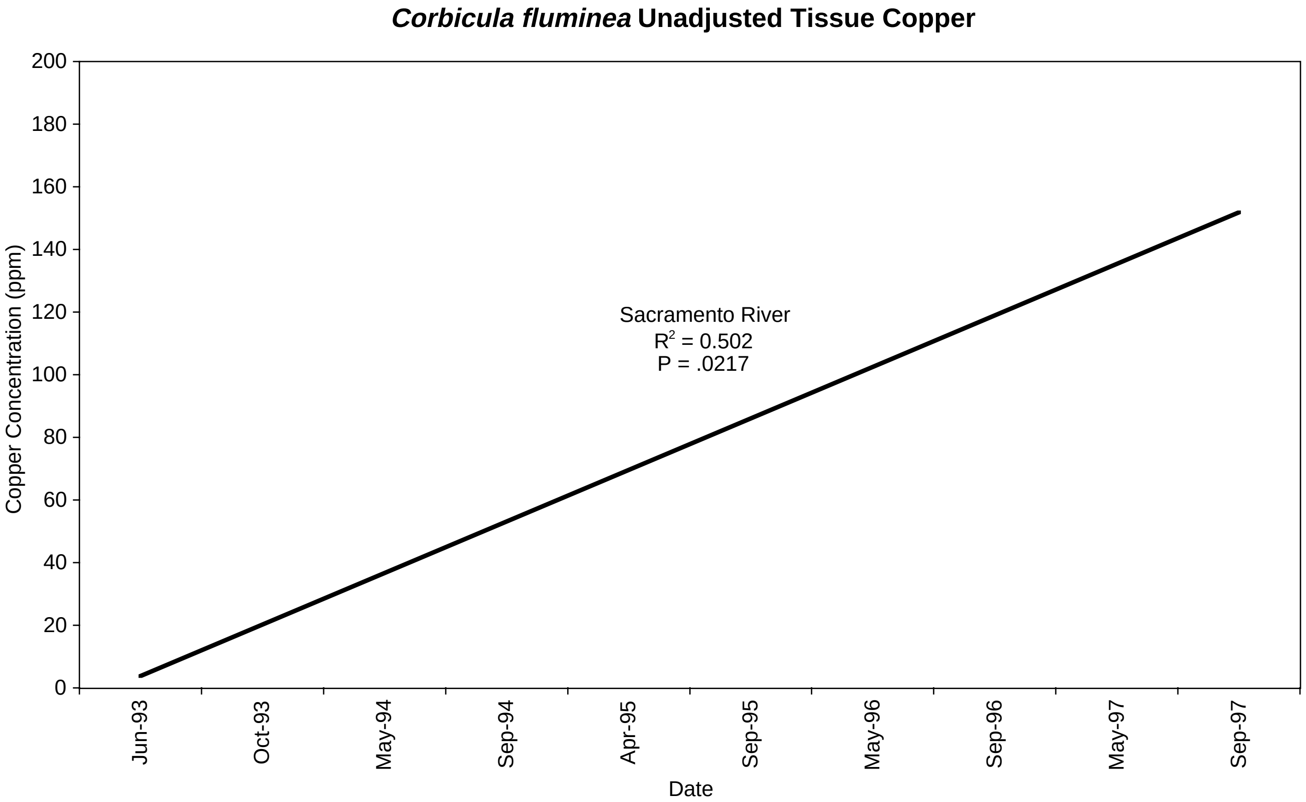

Figure 5.38. Trendlines for unadjusted copper in clams at one site between June 1993 and September 1997. The regression coefficient and probability for the trendline is indicated.

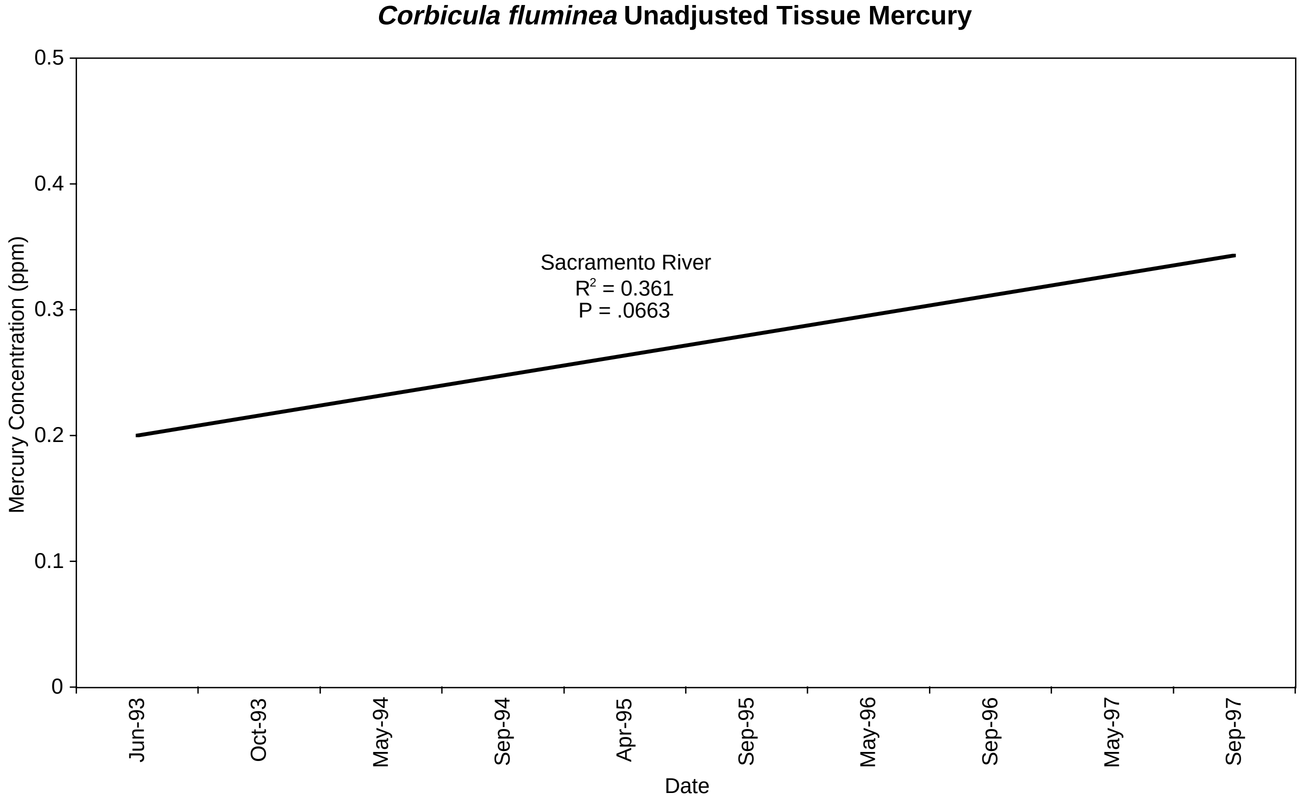

Figure 5.39. Trendlines for unadjusted mercury in clams at one site between June 1993 and September 1997. The regression coefficient and probability for the trendline is indicated.

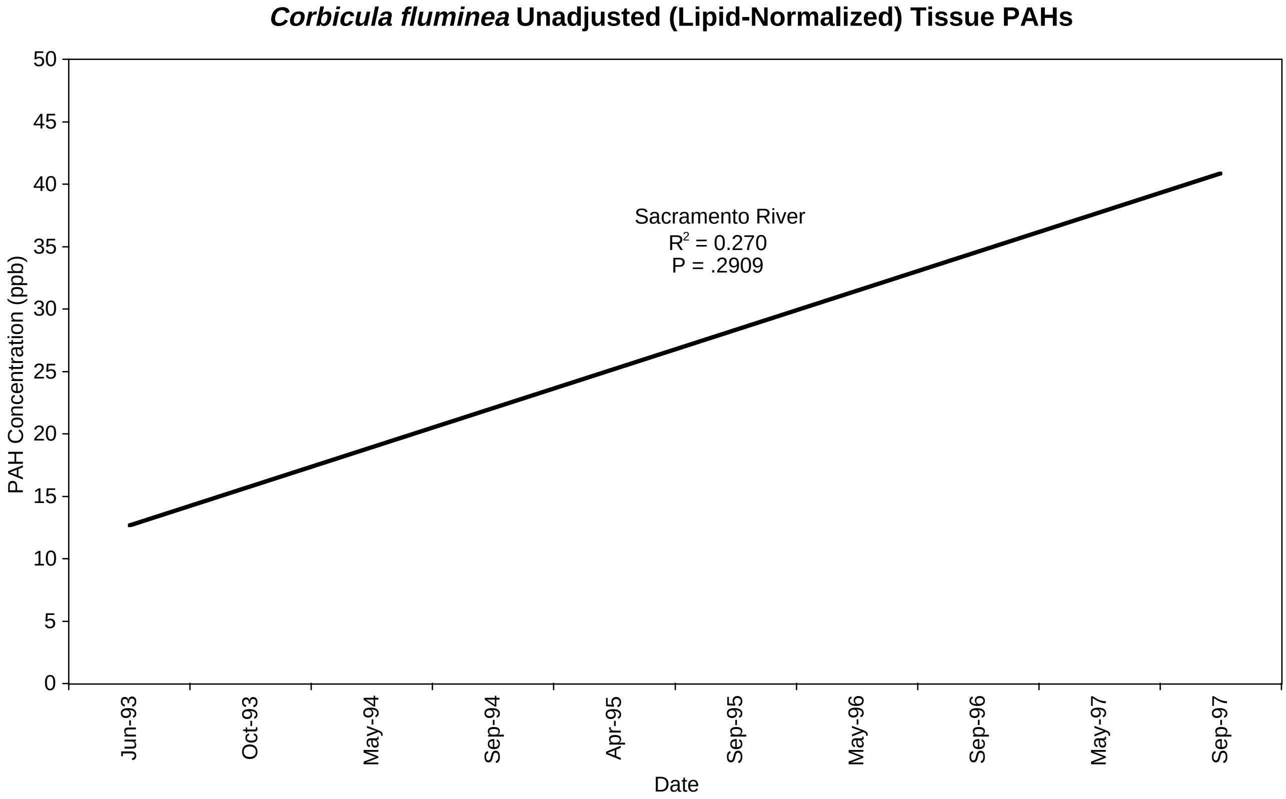

Figure 5.40. Trendlines for unadjusted (lipid-normalized) PAHs in clams at one site between June 1993 and September 1997. The regression coefficient and probability for the trendline is indicated.

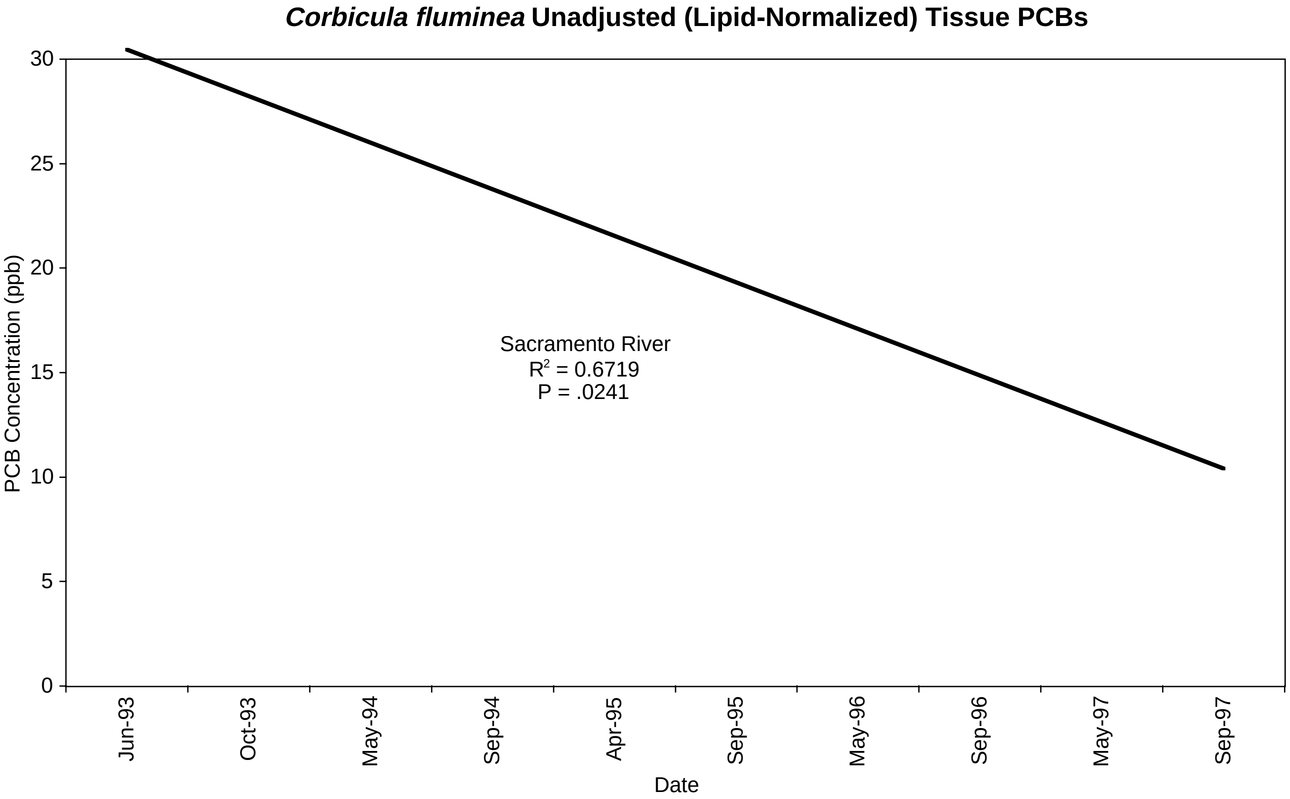

Figure 5.41. Trendlines for unadjusted (lipid-normalized) PCBs in clams at one site between June 1993 and September 1997. The regression coefficient and probability for the trendline is indicated.

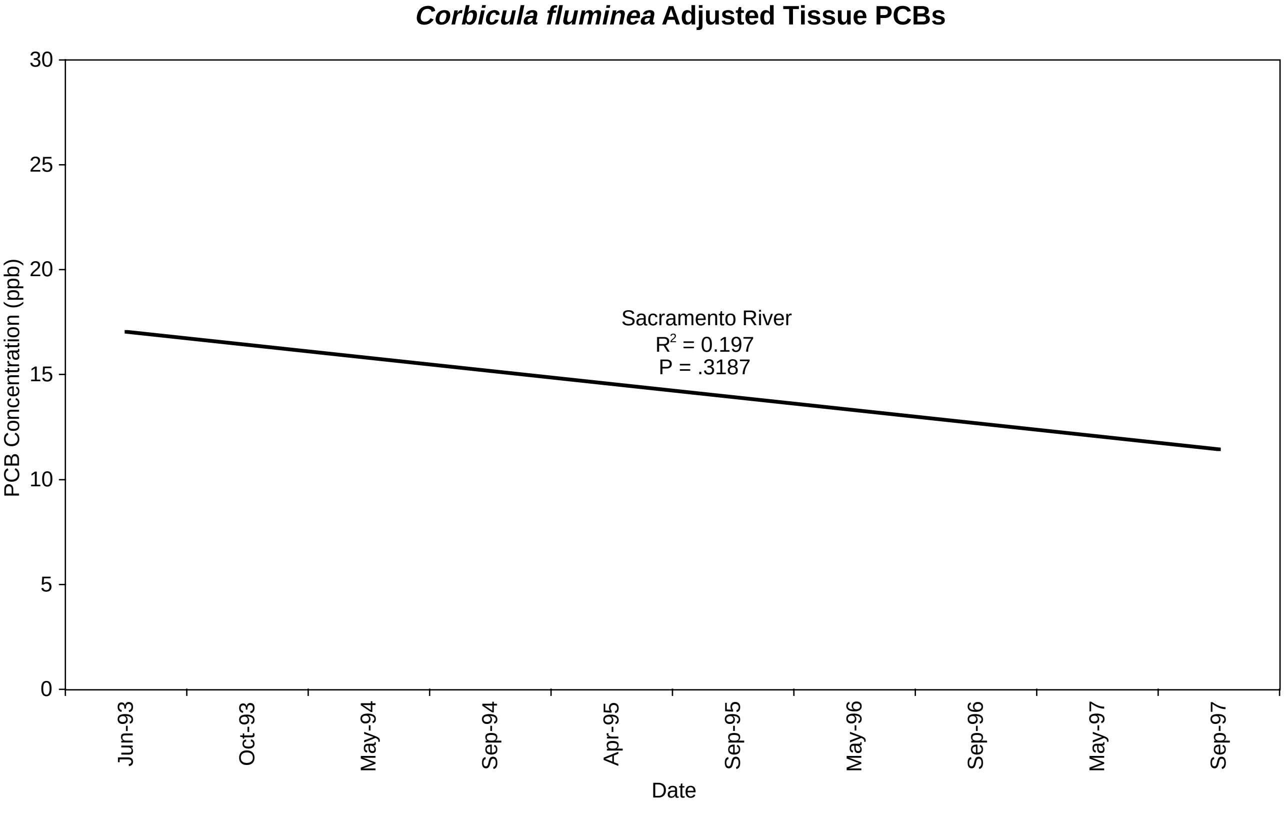

Figure 5.42. Trendlines for adjusted PCBs in clams at one site between June 1993 and September 1997. The regression coefficient and probability for the trendline is indicated.

2. Do the adjustments to tissue concentrations for suggested effects of water quality parameters improve the correspondence between tissue measurements and water measurements?
3. Do the bivalves consistently bioaccumulate certain contaminants from either the dissolved or particulate fractions?

Mussels

The tissue concentrations of very few contaminants were significantly related to either dissolved or particulate water fractions (Table 4 in *Appendix E*). The measured tissue concentrations of copper, mercury, and zinc were negatively related to particulate or dissolved fractions and five of the remaining 20 possible regressions indicated non-significant negative regressions, suggesting no effect of water measurements on the tissue measurements. Adjustment of tissue data for the effects of water quality parameters actually reduced the correspondence between water measurements and tissue measurements for silver and chlordane, although adjustment did provide a significant regression between tissue and the dissolved water fraction for chlordane. Adjusted tissue concentrations improved the correspondence between tissue and water PCBs, with a significant regression for the dissolved fraction.

No consistent relationship existed between either the adjusted or unadjusted tissue trace substances and the dissolved or particulate water fractions, although the dissolved fraction appeared more important. Eleven out of 23 possible regressions indicated either significant or non-significant positive correlations with the dissolved fraction, and four indicated significant or non-significant positive correlations with the particulate fraction. The remaining regressions indicated negative relationships with either dissolved or particulate fractions.

Oysters

Oysters were similar to mussels in the paucity of significant regressions between tissue concentrations and either water fraction (Table 5 in *Appendix E*). Only four contaminants had significant regressions for either adjusted or unadjusted tissue contaminants. The tissue concentrations of both copper and mercury exhibited negative correlations with the particulate fraction. Six of the remaining tissue trace substances indicated non-significant negative correlations with either dissolved or particulate fractions. Adjustment of tissue data for suggested effects of environmental variables decreased the correspondence to water measurements for PCBs, although both adjusted and unadjusted tissue data indicated positive correlations with dissolved water concentrations. None of the four cases of significant regressions indicated improved correspondence between water measurements and adjusted tissue concentrations.

Neither the dissolved nor the particulate fractions were predominant in their suggested effects on tissue concentrations. Three tissue trace substances indicated significant or non-significant positive correlations with the dissolved fraction and two indicated significant or non-significant positive correlations with the particulate fraction.

Clams

There were only four trace substances in clam tissues (mercury, selenium, PAH, PCB) that were significantly correlated with either dissolved or particulate water fractions on tissue concentrations (Table 6 in *Appendix E*), and one of them (selenium) was negatively correlated with the dissolved. Four tissue trace substances indicated non-significant negative correlations with either dissolved or particulate fractions. Adjustment of tissue data for suggested effects of environmental variables improved the correspondence to water measurements for mercury and PCB, although the significant regression for adjusted PCB included positive effects of the particulate fraction and negative effects of the dissolved fraction.

Unlike with the mussels and oysters, tissue trace substances were more often positively correlated with the particulate fraction than with the dissolved fraction. Seven tissue trace substances had either significantly or non-significantly positive correlations with the particulate fraction and only two had significantly or non-significantly positive correlations with the dissolved fraction.

Findings and Conclusions

1. Bivalves are effective tools for monitoring long-term trends, especially for bioaccumulative trace organics.
2. Bivalves are of limited use in monitoring trends for those trace elements that do not accumulate in tissues, as integrators of water contamination for mercury and arsenic, or for estimating mercury transfer to higher levels of the food web.
3. The comparisons of tissue and corresponding water concentrations reveal that time-integrated bioaccumulation of contaminants by bivalves generally does not correspond well to water measurements of contaminants made on one or two occasions during bivalve deployments. Although this conclusion is not necessarily surprising, it indicates that bivalves are important sampling devices and add information that water or sediment data alone would not supply.
4. Bivalves are but one of many tools to determine the transfer and potential magnification of contaminants to higher trophic levels. The current use of non-resident species appears suboptimal in this regard.
5. The bivalve data indicate spatial and temporal trends in contaminants that have important implications for management of the Estuary. Although PCB tissue concentrations seem to be decreasing at some stations, overall Estuary trends are not yet clear. For PCBs, the removal of natural environmental variables that may influence tissue trace substance data may reveal different patterns from the unadjusted data (e.g., temporal trends for mussels and clams). Other trace substances, when the suggested effects of environmental variables are statistically removed from tissue concentrations, may exhibit clearer trends than PCBs and will be investigated in the future. Tissue concentrations of PCBs are higher in the South Bay reach than in other reaches, thus mirroring the findings in water and sediment. Both mussels and clams indicate increases in copper in the Estuary. Whether this increase is due to increased copper loading to the Estuary from runoff or other causes is not immediately apparent. Perhaps most interestingly, the spatial and temporal trends evident with the mussels were not apparent in the oyster data. This emphasizes the importance of species selection in view of the management issues important for the Estuary. Bivalves serve as useful biomonitors for site comparisons (provided the same species can be deployed) in efforts to determine general pollutant sources or pathways.
6. The bivalve monitoring component includes measurements that theoretically lend themselves to evaluate contaminant effects on these indicators, such as growth, condition, and survival. While we are currently using bivalves merely as contaminant integrators and surrogates for pollutant measurements in the water column, they might also serve as response indicators to pollutants. Whether or not bivalves are an effective tool for evaluating pollutant effects remains to be assessed and will likely be introduced in the RMP re-design discussion.

Recommendations for Consideration in Re-design

1. Maintain the approach of using transplanted bivalves for long-term trend monitoring and as a relatively simple diagnostic tool of emerging pollutant problems, provided that the current analyte list is expanded to include bioaccumulative substances and other

contaminants that are currently not quantified but which are suspected to cause environmental problems.

2. Determine the potential application of a variety of bivalve species in pollutant source and pathway identifications.
3. Determine if bivalves are useful in the determination of pollutant effects.
4. Continue to explore the effects of environmental variables on bivalve health and bioaccumulation by collecting water data near bivalve deployment sites at the same depths as the bivalves.
5. Evaluate which indicator species should be used to assess contaminant transfer to higher trophic levels.

References

Absil, M.C.P., J.J. Kroon, and H.T. Wolterbeck. 1994. Availability of copper from phytoplankton and water for the bivalve *Macoma balthica*. 2. Uptake and elimination from ^{64}Cu-labelled diatoms and water. Marine Biology 118(1): 129–135.

Gunther, A.J. and J.A. Davis. 1997. An evaluation of bioaccumulation monitoring with transplanted bivalves in the RMP. *In* 1996 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. San Francisco Estuary Institute, Richmond, CA. pp. 187–200.

Gunther, A.J., J.A. Davis, D.D. Hardin, J. Gold, D. Bell, J.R. Crick, G.M. Scelfo, J. Sericano, and M. Stephenson. 1999. Long-term bioaccumulation monitoring with transplanted bivalves in the San Francisco estuary. Marine Pollution Bulletin 38(3):170–181.

Hebert, C.E. and K.A. Keenleyside. 1995. To normalize or not to normalize? Fat is the question. Envir. Tox. and Chem. 14:801–807

Hutchins, D.A., I. Stupakoff, and N.S. Fisher. 1996. Temperature effects on accumulation and retention of radionuclides in the sea star *Asterias forbesi*: Implications for contamination of northern waters. Marine Biology 125(4):701–706.

Luoma, S.N. and G.W. Bryan. 1982. A statistical study of environmental factors controlling concentrations of heavy metals in the burrowing bivalve *Scrobicularia plana* and the polychaete *Nereis diversicolor*. Estuarine, Coastal and Shelf Science 15(1):95–108.

Luoma, S.N. and R. Linville. 1996. A comparison of selenium and mercury concentrations in transplanted and resident bivalves from north San Francisco bay. *In* 1995 Annual Report: San Francisco Estuary Regional Monitoring Program for Trace Substances. San Francisco Estuary Institute, Richmond, CA. pp. 160–170.

Magni, P. 1993. Effect of oxygen concentration on the bioavailability of copper for the bivalve *Macoma balthica*. Instituut voor Oecologisch Onderzoek, Heteren, Netherlands. NTIS No. PB94110707XSP. 33p.

Russell, R.W. and F.A.P.C. Gobas. 1989. Calibration of the Fresh Water Mussel *Elliptio complanata* for quantitative biomonitoring of hexachlorobenzene and octachlorostyrene. Bull. Environ. Contam. Toxicol. 43:576–582.

Salazar M.H and S.M. Salazar. 1995. *In situ* bioassays using tranplanted mussels: 1. Estimating chemical expposure and bioeffects with bioaccumulation and growth. *In* J.S. Hughes, G.R. Biddinger, and E. Mones, (eds.), Third Symposium on Environemntal Toxicology and Risk Assessment, STP 1218. American Society for Testing and Materials, Philadelphia, 1994, pp. 216–241.

Salazar M.H and S.M. Salazar. 1998. Using cages bivalves as part on an expposure-dose-response triad to support and integrated risk assessment strategy. *In* Proceedings —Ecological Risk Assessment: A meeting of policy and science. A. de Peyster and K. Day, (eds.). SETAC Press, pp. 167–192.

Stephenson, M. 1992. A report on bioaccumulation of trace metals and organics in bivalves in San Francisco Bay. Submitted to California Regional Water Quality Control Board, San Francisco Bay Region. California Department of Fish and Game, Moss Landing Marine Labs, Moss Landing, CA.

Wang, W-X, N.S. Fisher, and S.N. Luoma. 1995. Assimilation of trace elements ingested by the mussel *Mytilus edulis*: Effects of algal food abundance. Marine Ecology Progress Series 129:165–176.

Wright, D.A. and C.D. Zamuda. 1987. Copper accumulation by two bivalve molluscs: Salinity effect is independent of cupric ion activity. Marine Environmental Research 23(1):1–14.