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Uptake of Environmental Contaminants by Small Mammals in Pickleweed Habitats at San Francisco Bay, California

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Abstract. Small mammals were live-trapped in pickleweed (*Salicornia virginica*) habitats near San Francisco Bay, California in order to measure the uptake of several contaminants and to evaluate the potential effects of these contaminants on the endangered salt marsh harvest mouse (*Reithrodontomys raviventris*). Tissues of house mice (*Mus musculus*), deer mice (*Peromyscus maniculatus*), and California voles (*Microtus californicus*) from nine sites were analyzed for chemical contaminants including mercury, selenium, cadmium, lead, and polychlorinated biphenyls (PCBs). Concentrations of contaminants differed significantly among sites and species. Mean concentrations at sites where uptake was greatest were less than maximum means for the same or similar species recorded elsewhere. Harvest mice (*Reithrodontomys spp.*) were captured only at sites where concentrations of mercury or PCBs were below specific levels in house mice. Additional studies aimed at the protection of the salt marsh harvest mouse are suggested. These include contaminant feeding studies in the laboratory as well as field monitoring of surrogate species and community structure in salt marsh harvest mouse habitats.

Human encroachment has fragmented and severely reduced in area the salt marsh habitat that once surrounded San Francisco Bay (Josselyn 1983). Chemical pollution of Bay waters is also extensive, and tidal flooding undoubtedly carries this pollution into marsh habitats. Flegal (1977) found that the macro-seston of the Bay contained high concentrations of mercury compared with other estuaries. Moyer and Budinger (1974) measured cadmium levels in low-tide shoreline sediments at 68 locations around the Bay and found the highest concentrations associated with a lead smelter and with oil refineries. Law and Goerlitz (1974) reported organochlorine insecticides and polychlorinated biphenyls (PCBs) in sediments from 26 streams entering the Bay; PCBs were as high as 1.4 μg/g (dry weight), and chlordane reached 0.8 μg/g. Luoma and Cloern (1982) concluded that "Localized instances of biological contamination with toxic metals and trace organics equal those anywhere in the world." Gunther *et al.* (1987) described and listed sources of metals, aromatic hydrocarbons, and chlorinated hydrocarbons entering the Bay. Phillips (1987) and Long *et al.* (1988) summarized temporal and geographic trends in contaminant loads in aquatic species from numerous Bay localities, and information about estuarine birds is also available (Ohlendorf *et al.* 1988; Ohlendorf and Fleming 1988; Ohlendorf and Marois 1990). Even with these findings at hand, much remains to be learned about concentrations of contaminants in, or their possible effects on, salt marsh wildlife.

Principal small-mammal species in pickleweed (*Salicornia virginica*) marsh habitats are house mouse (*Mus musculus*), salt marsh harvest mouse (*Reithrodontomys raviventris*), western harvest mouse (*Reithrodontomys megalotis*), deer mouse (*Peromyscus maniculatus*), California vole (*Microtus californicus*), ornate shrew (*Sorex ornatus*), and vagrant shrew (*S. vagrans*). The salt marsh harvest mouse is unique to the salt marshes of the San Francisco Bay region (Shellhammer 1982). For this reason and, more recently, because of its endangered status, the ecology of this mouse has been studied intensively (*e.g.*, Fisler 1965, 1971; Zetterquist 1977; Shellhammer *et al.* 1982; Hood *et al.* 1984; Nelson *et al.* 1984; Botti *et al.* 1986; Shellhammer 1989). However, data on contaminants in small mammals of the pickleweed marshes are limited to one report of lead, cadmium, selenium, and arsenic concentrations in house mice and California voles from the Concord Naval Weapons Station on the south shore of Suisun Bay (O'Neil 1988).

Our objectives were to measure selected contaminants in non-endangered small mammals from pickleweed marshes and evaluate whether these contaminants might have any adverse effects, including possible effects on salt marsh harvest mice living in the same marshes.

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Table 1. Small mammals captured in pickleweed marshes of San Francisco Bay, July 6–20, 1989

Site	Species					Trap-nights
	Harvest mouse	House mouse	Deer mouse	Calif. vole	Shrew	
Baumberg	0	1 (1,0)	5 (5,5)	0	0	125
Alameda Flood Control	0	1 (1,0)	8 (8,8)	0	0	125
Mare Island	8	5 (5,5)	0	3 (3,3)	1	247
Benicia	2	2 (1,0)	0	0	0	248
Castro Cove	6	12 (9,9)	0	2 (2,0)	0	348
Lower Tubbs	3	3 (3,3)	3 (3,3)	1 (1,0)	0	123
China Camp	4	0	35 (10,10)	1 (1,0)	0	123
Newark Slough	0	8 (8,8)	0	0	0	245
Alviso	4	2 (2,0)	0	0	0	486
Crittenden Marsh	9	5 (5,5)	0	0	0	242
Bair island	3	0	0	2 (2,0)	0	242
Calaveras Point	0	4 (4,4)	0	3 (3,3)	0	240
Totals	39	43 (39,34)	51 (26,26)	12 (12,6)	1	2,794

Note: Harvest mice (*Reithrodontomys raviventris* and *R. megalotis*) and the ornate shrew (*Sorex ornatus*) were released where captured; 39 house mice (*Mus musculus*), 26 deer mice (*Peromyscus maniculatus*), and 12 California voles (*Microtus californicus*) were kept for chemical and histopathological analyses. The numbers of mice examined histopathologically and the subset analyzed chemically are indicated, respectively, in parentheses

Materials and Methods

Small mammals were trapped at 12 sites (Table 1, Figure 1) from July 6 to July 20, 1989, along the southern and northern (San Pablo Bay) portions of the San Francisco Bay area. Habitat at all sites was salt marsh, dominated by pickleweed. Traps were set in higher pickleweed marsh areas near the peripheral halophyte zone to avoid tidal inundation. [See Josselyn (1983) for a complete description of plant composition and zonation in Bay marshes.] Salt marsh harvest mice were trapped in the 1970s or 1980s at all 12 sites except Crittenden Marsh (Geissel *et al.* 1988; San Francisco Bay National Wildlife Refuge, unpublished records), and this species were thought likely to be found in Crittenden Marsh because of this site's habitat characteristics and location. Habitat of the salt marsh harvest mouse has been described elsewhere (Fisler 1965; Shellhammer 1977; U.S. Fish and Wildlife Service 1984; Botti *et al.* 1986).

Sherman live-traps (7.6 by 7.6 by 25.4 cm) were baited with a mixture of rolled oats and peanut butter; cotton balls were added for insulation. Traps were set in late afternoon or early evening and checked the following morning. Usually two nearby sites were trapped each night. Traps were moved daily except for two sites (Benecia State Park and Alviso), where traps were operated on two consecutive nights. To increase sample size at two sites (Mare Island and Castro Cove), trapping was done a second time within 3 days and on contiguous pickleweed marsh habitat. Up to nine mice each of the house mouse, California vole, and deer mouse were kept from each site (Table 1); mammals of other species were released where captured. Most of the harvest mice captured are belived to have been *R. raviventris,* but positive assignment to species was not attempted.

Mice were asphyxiated with carbon dioxide in field laboratories at the San Francisco Bay National Wildlife Refuge in Fremont and at the California Maritime Academy in Vallejo. Small sections of liver and kidney were removed and placed in buffered formalin under chemically clean conditions for later histopathological analysis; the remainder of each mouse was immediately frozen. Later, at the Patuxent Wildlife Research Center, mice were thawed, and livers, kidneys, and female reproductive tracts were removed and carcasses dissected under chemically clean conditions. Livers, kidneys, and carcasses were refrozen to await chemical analysis. If three mice of the same species were caught at a site, the liver, kidneys, and carcass (= whole mouse minus skin, head, feet, tail, gastrointestinal tract, liver, kidneys, and female reproductive tract) of each mouse were analyzed separately for contaminants. If more than three mice of the same species were caught, tissues were combined to form three pools each of livers, kidneys, and carcasses for chemical analysis. Pools included tissues from up to four mice. If fewer than three mice were caught, none was analyzed chemically. Reproductive tracts were examined for embryos, preserved in formalin, and later examined for uterine scars. Histopathological examinations were conducted by Donald A. Willigan, Inc. of Germantown, Maryland.

Contaminants were selected for analysis because of their toxicity to wildlife and known occurrence in the Bay. Liver and kidney samples were analyzed for metals and selenium by the Center for Environmental Measurements, Research Triangle Park, North Carolina. Liver samples were analyzed for mercury and selenium, kidney samples for cadmium and lead. Samples were homogenized with a food processor, and then portions were freeze dried for moisture determination and acid digestion. Analyses for mercury were by cold vapor atomic absorption (CVAA), wherein 0.25–0.50 g of freeze-dried tissue was refluxed for 2 h in 10 ml nitric acid and diluted to 50 ml with 1% HCl. Mercury was measured with an Instrumentation Laboratories Model 251 atomic absorption spectrophotometer; tin chloride was used as reducing agent. Lower limit of detection was 0.04 μg/g (dry weight), and average recovery from spiked tissue samples was 96%. Results were not corrected for recovery.

Analyses for selenium, cadmium, and lead were by graphite furnace atomic absorption (GFAA), wherein 0.25–0.50 g of freeze-dried tissue was heated by microwave oven in a capped 120-ml Teflon vessel with 5 ml of nitric acid for 3 min at 120 W, 3 min at 300 W, and 15 min at 450 W. The residue was diluted to 50 ml with distilled, deionized water. Selenium, cadmium, and lead were measured with a Perkin Elmer Zeeman 3030 atomic absorption spectrophotometer with an HGA-600 graphite furnace and As-60 autosampler. Lower limits of detection were 0.6 (selenium), 0.08 (cadmium), and 0.8 (lead) μg/g (dry weight). Average recoveries from spiked mouse tissue samples were 102% (selenium) and 100% (lead); there was insufficient kidney tissue to spike cadmium. Mercury, selenium, cadmium, and lead concentrations are reported as μg/g dry weight. Results were not corrected for recovery.

Carcass samples were anlyzed for organochlorine contaminants by the Mississippi State Chemical Laboratory, Mississippi State, Mississippi. Carcass samples (4.7–10 g) were ground with anhydrous sodium sulfate and Soxhlet-extracted with hexane for 7 h. The extract was evaporated to dryness, dissolved in petroleum ether, and extracted four

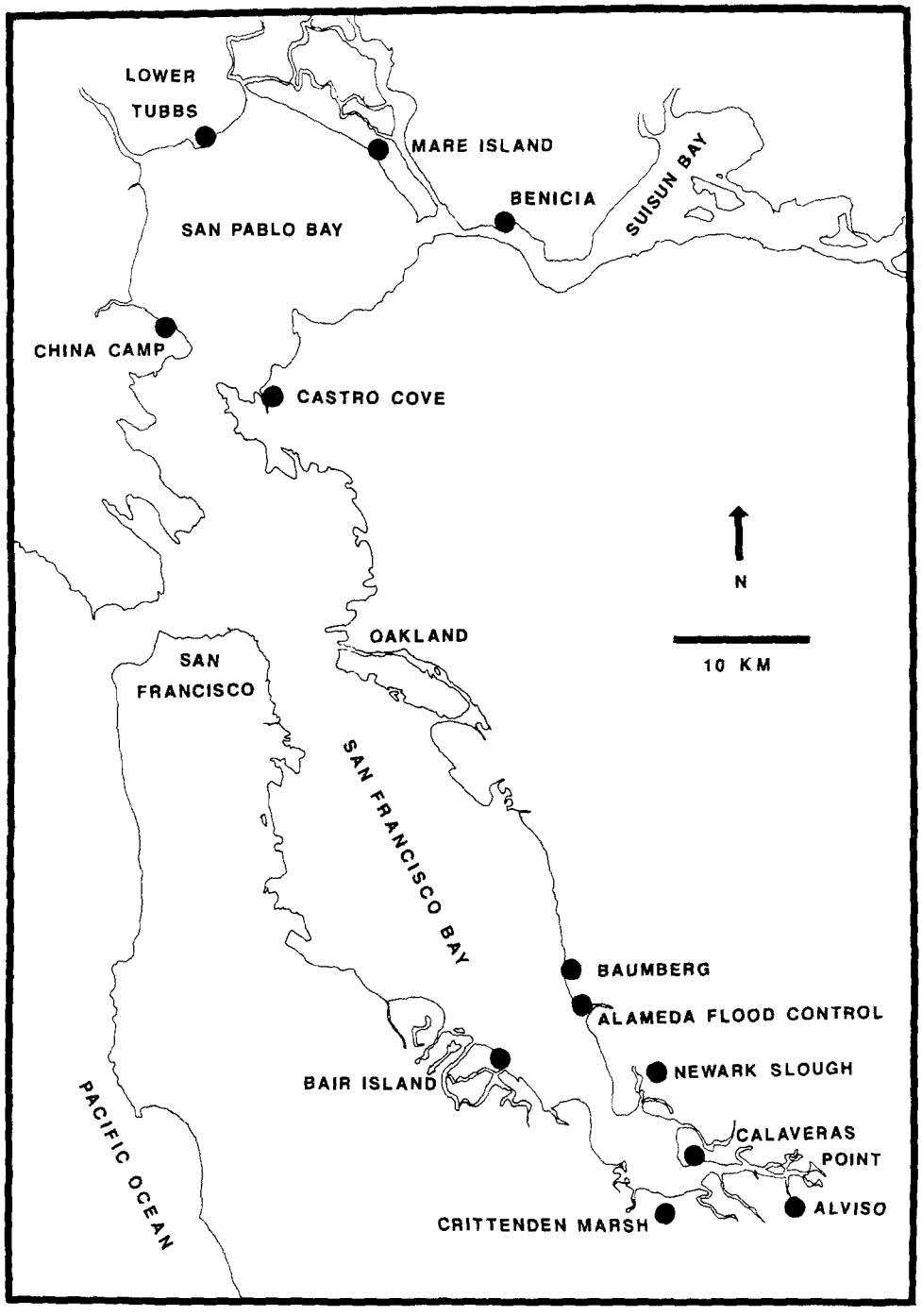

Fig. 1. Sites where small mammals were collected in pickleweed marshes near San Francisco Bay, California, July 6–20, 1989

times with acetonitrile which was saturated with petroleum ether. Residues were transferred to a glass chromatographic column contaning 20 g of Florisil®. The column was eluted with 200 ml of 6% diethyl ether: 94% petroleum ether (Fraction I) followed by 200 ml of 15% diethyl ether: 85% petroleum ether (Fraction II). Fraction II was concentrated for quantification of residues by packed or capillary column electron capture gas chromatography. Fraction I was concentrated and transferred to a silicic acid chromatographic column for cleanup required to separate PCBs from other organochlorines. Each of three fractions from the silicic acid column was concentrated before quantification of organochlorine residues by packed or megabore column electron capture gas chromatography. Lower limits of detection were 0.01 μg/g (wet weight) except for PCBs, which were 0.05 μg/g (wet weight). Average recoveries from spiked mouse tissue ranged from 77 to 93% except for HCB (hexachlorobenzene), which was 58%. Organochlorine concentrations are reported as μg/g wet weight. Results were not corrected for recovery.

Geometric means were calculated because of skewness in the contaminant data. Concentrations below the limit of detection entered calculations as one-half the detection limit. Log-transformed data were analyzed by one-way analysis of variance with pairwise comparisons performed with Tukey's multiple comparison method (Neter and Wasserman 1974). Before regresson analyses, percentages of species in total capture samples were arcsin-transformed to equalized variances. Those literature data for mercury, selenium, cadmium, and lead in soft tissues reported as μg/g wet weight were converted to approximate μg/g dry weight equivalents by multiplication by 3.5 (Talmage and Walton 1991) before comparison with our data. Arithmetic means

Table 2. Comparisons among sites within species of geometric mean concentrations of metals (ppm dry weight), selenium (ppm dry weight), and PCBs (ppm wet weight) in mice from sites near San Francisco Bay

Liver		Kidney		Carcass
Mercury	Selenium	Cadmium	Lead	PCBs
Mus musculus (house mouse)				
CP 3.95[a]	CP 4.75[a]	CP 3.09[a]	CC 9.77[a]	CP 0.42[a]
NS 0.42[b]	CM 3.85[ab]	MI 1.71[ab]	MI 2.02[ab]	NS 0.10[ab]
CM 0.19[bc]	CC 3.81[ab]	CM 0.71[abc]	CM 1.96[ab]	CM 0.06[ab]
CC 0.07[bc]	NS 2.62[ab]	CC 0.55[bc]	LT 1.57[ab]	LT 0.02[b]
LT 0.03[c]	LT 1.58[b]	NS 0.54[bc]	NS 1.19[ab]	CC 0.02[b]
MI 0.02[c]	MI 1.54[b]	LT 0.30[c]	CP 0.79[b]	MI 0.02[b]
Peromyscus maniculatus (deer mouse)				
BA 1.08[a]	BA 3.53[a]	BA 2.11[a]	BA 1.92[a]	BA 0.22[a]
AF 0.35[a]	LT 3.10[a]	LT 1.06[a]	LT 1.50[a]	AF 0.04[b]
CH 0.06[a]	AF 2.54[a]	AF 0.61[a]	AF 0.69[a]	CH 0.02[b]
LT 0.05[a]	CH 2.32[a]	CH 0.40[a]	CH 0.60[a]	LT 0.02[b]
Microtus californicus (California vole)				
CP 0.12[a]	CP 1.56[a]	MI 5.46[a]	MI 6.27[a]	CP 0.02[a]
MI 0.02[b]	MI 0.54[a]	CP 0.39[b]	CP 0.74[b]	MI 0.02[a]

Note: Samples analyzed chemically contained tissues of 1 to 4 individuals; sample sizes for means are 3 except for Calaveras Point kidney samples from house mice where they are 2 due to a lost sample. Abbreviations are: AF, Alameda Flood Control; BA, Baumberg; CC, Castro Cove; CH, China Camp; CM, Crittenden Marsh; CP, Calaveras Point; LT, Lower Tubbs; MI, Mare Island; NS, Newark Slough. Means in the same column sharing the same superscript letters are not different ($p < 0.05$) by Tukey's method (Neter and Wasserman 1974)

(= common averages) were also calculated for certain of our contaminant data to allow comparison with similarly calculated means from the literature.

Results

Captures and Chemical Data

One hundred forty-six mammals of five species were trapped at 12 sites during 2,794 trap-nights (Table 1). Of this total, 39 house mice, 26 deer mice, and 12 California voles were killed and examined histologically, and of these, 34 house mice, 26 deer mice, and 6 voles were analyzed, either singly or in pools, for chemical contaminants. Insufficient numbers of animals for analysis were captuerd at Alviso, Benicia, and Bair. Among 36 carcass samples, 10 contained measureable PCBs, 13 contained DDE, 2 contained oxychlordane, 4 contained *trans*-nonachlor, and 3 contained dieldrin, but only results for PCBs are presented. Oxychlordane, *trans*-nonachlor, and dieldrin are not considered further because of their infrequent occurrence (maximum concentrations were 0.02, 0.04, and 0.04 μg/g wet weight, respectively.) DDE is not considered because the highest concentration was only 0.03 μg/g (wet weight), and the other 12 measured values were all 0.01 μg/g. Measurable concentrations of selenium and metals were found in most samples—selenium in 97% of samples, mercury in 80%, cadmium in 100%, and lead in 94%.

Contaminant Differences Among Sites

The mean concentration of mercury was significantly highest at Calaveras Point for both house mice and voles (Table 2). Mean selenium and PCBs also tended to be higher at this site, as well as at other sites in the southern part of the Bay. In voles, lead was significantly higher at Mare island than at Calaveras Point, but the maximum mean concentration of lead was in house mice at Castro Cove. In voles, cadmium was significantly higher at Mare Island than at Calaveras Point. Among the 14 maximum mean concentrations (5 contaminants each in 3 species, but with no maximum for PCBs in voles; see Table 2), 6 were from Calaveras Point, 5 from Baumberg, 2 from Mare Island, and 1 from Castro Cove. Thus, 11 of 14 (79%) maxima were from the southern Bay. Among the 14 minimum mean concentrations, 5 were Mare Island, and 3 each were from Lower Tubbs, Calaveras Point, and China Camp. Thus, 11 of 14 (79%) minima were from the northern Bay.

Maximum single-sample chemical concentrations with collection sites, species, and number of mice in the sample were: mercury, 4.5 μg/g, Calaveras Point, house mouse (1); selenium, 5.2 μg/g, Calaveras Point, house mouse (2); cadmium, 16 μg/g, Mare Island, California vole (1); lead, 14 μg/g, Castro Cove, house mouse (3); PCBs, 0.45 μg/g, Calaveras Point, house mouse (2).

Contaminant Differences Among Species

At the three sites for which there was sufficient data, house mice contained higher contaminant concentrations than California voles in four of five mean comparisons that were statistically significant (mercury, selenium, cadmium and PCBs), and deer mice had higher cadmium residues than house mice in the one significant comparison between these two species (Table 3).

Contaminants Versus Species Occurrence

House mice from six sites were available in sufficient numbers for contaminant analyses. Examination of species composition

Table 3. Comparisons between species within sites of geometric mean concentrations of metals (ppm dry weight), selenium (ppm dry weight), and PCBs (ppm wet weight) in mice from three localities near San Francisco Bay

Liver		Kidney		Carcass
Mercury	Selenium	Cadmium	Lead	PCBs
Calaveras Point				
MM 3.95[a]	MM 4.75[a]	MM 3.09[a]	MM 0.79[a]	MM 0.42[a]
MC 0.12[b]	MC 1.56[b]	MC 0.39[b]	MC 0.74[a]	MC 0.02[b]
Mare Island				
MM 0.02[a]	MM 1.54[a]	MC 5.46[a]	MC 6.27[a]	MC 0.02[a]
MC 0.02[a]	MC 0.54[a]	MM 1.71[a]	MM 2.02[a]	MM 0.02[a]
Lower Tubbs				
PM 0.05[a]	PM 3.10[a]	PM 1.06[a]	MM 1.57[a]	PM 0.02[a]
MM 0.03[a]	MM 1.58[b]	MM 0.30[a]	PM 1.50[a]	MM 0.02[a]

Note: Samples analyzed chemically contained tissues of 1 to 2 individuals; sample sizes for means are 3 except for Calaveras Point kidney of house mice where they are 2 due to a sample lost at the analytical laboratory. MM, *Mus musculus* (house mouse); MC, *Microtus californicus* (California vole); PM, *Peromyscus maniculatus* (deer mouse). Means in the same column sharing the same superscript letter are not different ($p < 0.05$) by Tukey's method (Neter and Wasserman 1974)

of the small-mammal samples from these six sites in relation to mean amounts of contaminants found in the house mice showed that harvest mice were captured only at sites where concentrations of mercury or PCBs in the house mice were below specific levels (Figure 2). Harvest mice were captured at four sites where mercury concentrations in livers of house mice were ≤ 0.19 μg/g (dry weight) and carcass PCB concentrations were ≤ 0.06 μg/g (wet weight). Note that there was a strong positive relationship between mercury and PCB levels in house mice ($r = 0.99$, $p = 0.0001$).

Histopathology

Liver conditions that were possibly contaminant induced were cytoplasmic vacuolation (4 cases), multinucleate cells (1 case), multiple adenomatoid foci of cell hyperplasia (1 case), and minute discrete foci of cell necrosis (5 cases). The kidney condition of chronic nephritis (2 cases) was also found. Among the three species, 9 of 39 house mice (23.1%), 2 of 26 deer mice (7.7%), and 2 of 12 California voles (16.7%) had one of these pathological conditions, but the differences in these ratios were not significant ($X^2 = 2.63$, $p = 0.27$). No significant relationships were found between incidence of histopathologies and contaminant concentrations.

Litter Size

Counts of uterine scars and embryos yielded mean (± SE) litter sizes of 6.2 ± 0.2 (range = 6−7, n = 4) for house mice, 4.7 ± 0.7 (range = 3−7, n = 6) for deer mice, and 3.4 ± 0.2 (range = 3−4, n = 5) for California voles. Data were insufficient to make site comparisons. These litter sizes are similar to those reported by other investigators (Ingles 1965; Jameson and Peeters 1988).

Discussion and Conclusions

Possible Sources of Bay Contaminants

Elevated concentrations of cadmium and lead in mice at Mare Island may have come from a lead-slag fuming plant that operated at Selby near Carquinez Straits for >60 yr and produced airborne wastes that were thought responsible for deaths of horses in the Vallejo area (Moyer and Budinger 1974). Shipbuilding and repair at Mare Island Naval Shipyard also may be a source of cadmium pollution (Moyer and Budinger 1974). High concentrations of lead in mice at Castro Cove may be due to wastes from the oil refinery located at this site. The authors know of no natural or industrial source of mercury near Calaveras Point; however, because mercury is found in sewage discharge (Gunther *et al.*, 1987), such waste from the nearby cities of San Jose and Sunnyvale is a potential source. Also, Luoma and Cloern (1982) pointed out that runoff from old mercury mines carried wastes into creeks in this region.

How Do Contaminant Concentrations in Bay Mice Compare with Elevated Concentrations in Mice Elsewhere?

O'Neil (1988) reported concentrations of cadmium, lead, and selenium in tissues of house mice and California voles collected in 1985 at the Concord Naval Weapons Station on the south shore of Suisun Bay. Both estuarine marsh collection sites contained pickleweed and had been contaminated by military activities. Maximum means for cadmium and selenium in house mice of 3.50 and 1.33 μg/g (dry weight) were similar to or less than our highest means (arithmetic) of 3.10 and 4.76 μg/g from Calaveras Point in the same tissues. However, mean values for lead of 42.3 and 274 μg/g (dry weight) in house mice from both contaminated sites at Concord greatly exceeded our maximum mean (arithmetic) of 10.2 μg/g at Castro Cove. Our maxima for voles were slightly highter than values from Concord; however, because no value was reported for lead from the most contaminated Concord site, a meaningful comparison for lead is not possible.

Lead in kidneys of house mice from an Illinois roadside with traffic of 19,600 vehicles per day (vpd) averaged 8.1 μg/g (dry weight; Getz *et al.* 1977), which resembles our maximum of 10.2 μg/g; the maximum mean value for deer mice (9.0 μg/g) exceeded our value (3.43 μg/g, arithmetic mean) from Baumberg. Kidneys of deer mice from a Colorado roadside (38,000 vpd) contained 23 μg/g lead (median dry weight; Welch and Dick 1975), greatly exceeding our value from Baumberg of 1.92 μg/g (geometric mean).

The highest mean concentration of cadmium in kidneys of meadow voles *(Microtus pennsylvanicus)* from Ohio fields treated with sewage sludge was 23 μg/g (dry weight; Anderson et al.1982), which exceeds our maximum of 7.58 μg/g (arithmetic mean) for the California vole at Mare Island. The highest mean concentration of cadmium in white-footed mice *(Peromyscus leucopus)* was 2.31 μg/g (dry weight) in Pennsylvania where sewage sludge was applied to forested site (Anthony and Kozlowski 1982). This concentration resembles the maximum of 2.28 μg/g (arithmetic mean) for deer mice at Baumberg.

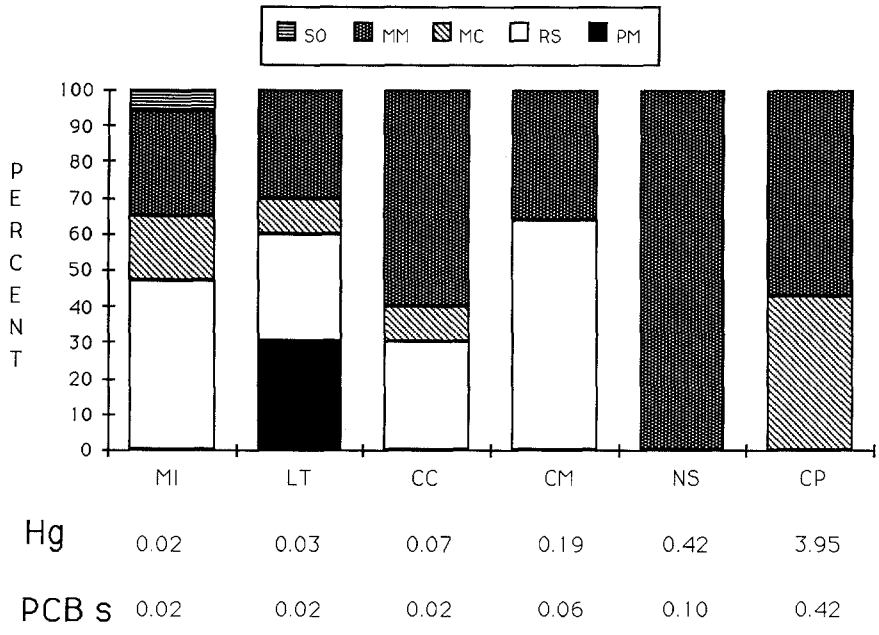

Fig. 2. Percentages of small mammal species in samples from six sites near San Francisco Bay in relation to concentratins of mercury (ppm dry weight) in house mouse livers and PCBs (ppm wet weight) in house mouse carcasses. CC, Castro Cove; CM, Crittenden Marsh; CP, Calaveras Point; LT, Lower Tubbs; MI, Mare Island; NS, Newark Slough; SO, *Sorex ornatus* (ornate shrew); MM, *Mus musculus* (house mouse); MC, *Microtus californicus* (California vole); RS, *Reithrodontomys spp.* (harvest mice); PM, *Peromyscus maniculatus* (deer mouse)

The highest mean concentration of mercury in livers of *Peromyscus* spp. from Canadian fields where mercury-treated seed was used was 0.808 μg/g (dry weight; Fimreite *et al.* 1970), whereas deer mice at Baumberg contained 1.19 μg/g (arithmetic mean). However, livers of long-tailed field mice *Apodemus sylvaticus)* from a British wheat field where mercury-treated seed had been used contained an averge 7.75 μg/g mercury (dry weight; Jefferies and French 1976), a concentration exceeding the highest mean (3.98 μg/g, arithmetic mean, in house mice at Calaveras Point) found in our study.

Selenium from agricultural irrigation drainage water accumulated in the aquatic ecosystem at Kesterson National Wildlife Refuge, California, causing lethal and reproductive effects in aquatic birds (Ohlendorf 1989). The highest mean concentrations of selenium in liver of 14.5 and 119 μg/g (dry weight, geometric means) for house mice and California voles at Kesterson (Clark 1987) exceeded those (4.75 μg/g in house mice and 1.56 μg/g in California voles at Calaveras Point) found in our study. Also, the liver of a single deer mouse at Kesterson contained 60 μg/g selenium.

Concentrations of total PCBs in whole bodies of white-footed mice collected near a contaminated Michigan pond averaged 2.32 μg/g (wet weight; Batty *et al.* 1990). This concentration is well above our maximum mean for deer mice (0.23 μg/g, arithmetic mean) at Baumberg, and is also exceeds the maximum mean of 0.42 μg/g (house mice at Calaveras Point) found in our study. Carcasses of the Michigan mice were not skinned, but it is doubtful that this difference in methodology had an appreciable effect on the analytical results.

Even though literature values were not found for all five contaminants in all three species, these comparisons with previously published data suggest that the contaminants studied at San Fransisco Bay were not at concentrations beyond levels reached elsewhere in the same, or at least similar, species.

Are These Contaminant Burdens Harmful to Bay Mice?

The presence and good health (judged from their active behavior in traps and good flesh condition at dissection) of the sampled mice at various Bay sites indicates a lack of harmful contaminant effects on these species at these sites. Also, the studies that showed higher mean residue concentrations than found in the present study in the same or similar species (Welch and Dick 1975; Jefferies and French 1976; Anderson *et al.* 1982; Clark 1987) found no negative effects associated with these higher concentrations, except that PCBs may have inhibited reproduction in white-footed mice at a site in Michigan (Batty et al. 1990). Further, the maximum individual sample values measured for each contaminant in the present study were all well below the maximum means found in the literature. Therefore, the evidence indicates that the species collected in the present study were well able to tolerate the contaminants present at the sites where they were found. But what about sites where some species were not captured?

Why Might Occurrence of Harvest Mice Vary with Levels of Contaminants?

Among the house mouse contaminant concentrations used as a basis for comparing sites (Figure 2), note that neither mercury nor PCBs was exceptionally high, nor were sharp increases evident between sites where harvest mice were caught and sites where they were not caught. However, because neither the amounts accumulated by harvest mice nor their toxicological reactions to these contaminants are known, the data for house mice could be indicative of harmful concentrations in harvest mice. If our data in Figure 2 indicate negative effects on harvest mice and are not the result of undetected habitat differences or chance, there may be three possible explanations for the absence of harvest mice at some sites: (1) house mice, which may be secondarily associated with contaminants because of their physical association with human activities, have reduced or excluded harvest mice through competition; (2) unkown factors correlated with the presence of contaminants have reduced or eliminated harvest mice; or (3) toxic effects of contaminants have reduced or eliminated harvest mice or their food sources.

Relative to the first explanation, our data showed no indication that occurrence of harvest mice varied in relation to house

mice. Also, other workers found that western harvest mice and house mice compete equally (Catlett and Shellhammer 1962), so one probably would not replace the other. Therefore, the first explanation seems unsupportable.

The second explanation proposes that contaminant concentrations as measured in this study may only be correlated with the real causal factors. For example, factors such as nutrient content or salinity of Bay waters may correlate positively with contaminant loads, but it may be effects of these noncontaminant factors on the species structure of the plant community or on the nutrient content of the plants that are critical to whether certain mouse species survive. Or, other correlated but unmeasured industrial or agricultural chemicals may have direct toxic effects on the mice or indirect effects through the plant community.

The third explanation would constitute a more direct reason for the apparent absence of harvest mice in relation to increased amounts of mercury and PCBs; however, our evidence is only indicative. It is intiutive that (1) chemical contamination of a site could increase to the point that all small mammals would be eliminated, (2) lesser contamination would eliminate only the more sensitive species, and (3) gradually increasing contamination would tend to eliminate species in order of decreasing sensitivity. Among the small mammal species of the pickleweed marsh, it also seems probable that the house mouse might be best adapted to withstand chemical contaminants because of its long commensal association with humans. Because harvest mice were not analyzed for contaminants in our study amd because there are no literature data available for these contaminants in harvest mice, it is not possible to evaluate potential effects. Present data are insufficient to reach any conclusions regarding chemical contamination and small-mammal community structure.

Recommendations

It is impossible to conclude from these results whether the salt marsh harvest mouse is threatened by contaminants, but if the strategy of saving this species by preserving habitats that presently contain these mice (U.S. Fish and Wildlife Service 1984) is to succeed, more data may be required about the threat from contaminants. The proposed research on pollution effects (U.S. Fish and Wildlife Service 1984) should include laboratory feeding studies to determine lethal and reproductive toxicities of common toxic agents, including mercury and PCBs, to salt marsh harvest mice, deer mice, and house mice. Based on these studies, relative toxicities among contaminants and among species will be identified, and these toxicities can be related to dietary dosage levels and tissue concentrations. It would be adviseable to make periodic collections and chemical analyses of house mice, deer mice, or California voles from critical salt marsh harvest mouse areas to monitor changes in contaminant concentrations and to determine whether harvest mice disappear when contaminants increase. The potential use of small mammal conmmunities as indicators of contamination based on which species are present or absent should be researched.

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References

Anderson TJ, Barrett GW, Clark CS, Elia VJ, Majeti VA (1982) Metal concentrations in tissues of meadow voles from sewage sludge-treated fields. J Environ Qual 11:272–277

Anthony RG, Kozlowski R (1982) Heavy metals in tissues of small mammals inhabitating waste-water-irrigated habitats, J Environ Qual 11:20–22

Batty J, Leavitt RA, Biondo N, Polin D (1990) An ecotoxicological study of a population of the white-footed mouse *(Peromyscus leucopus)* inhabiting a polychlorinated biphenyls-contaminated area. Arch Environ Contam Toxicol 19:283–290

Botti F, Warenycia D, Becker D (1986) Utilization by salt marsh harvest mice *Reithrodontomus raviventris halicoetes* of non-pickleweed marsh. Calif Fish Game 72:62–64

Catlett RH, Shellhammer HS (1962) A comparison of behavorial and biological characteristics of house mice and harvest mice. J Mamm 43:133–144

Clark DR Jr (1987) Selenium accumulation in mammals exposed to contaminated California irrigation drainwater. Sci Total Environ 66:147–168

Fimreite N, Fyfe RW, Keith JA (1970) Mercury contamination of Canadian prairie seed eaters and their avian predators. Can Field Nat 84:269–276

Fisler GF (1965) Adaptations and speciation in harvest mice of the marshes of San Fransisco Bay. Univ California Publ Zool 77:1–108

——(1971) Age structure and sex ratio in populations of *Reithrodontomys*. J Mamm 52:653–662

Flegal AR (1977) Mercury in the seston of the San Francisco Bay estuary. Bull Environ Contam Toxicol 17:733–738

Geissel W, Shellhammer H, Harvey HT (1988) The ecology of the salt-marsh harvest mouse *(Reithrodontomys raviventris)* in a diked salt marsh. J Mamm 69:696–703

Getz LL, Verner L, Prather M (1977) Lead concentrations in small mammals living near highways. Environ Pollut 13:151–157

Gunther AJ, Davis JA, Phillips DJH (1987) An assessment of the loading of toxic contaminants to the San Fransico Bay-Delta. Aquatic Habitat Institute, Richmond, CA, 330pp

Hood CS, Robbins LW, Baker RJ, Shellhammer HS (1984) Chromosomal studies and evolutionary relationships of an endangered species, *Reithrodontomys raviventris*. J Mamm 65:655–667

Ingles LG (1965) Mammals of the Pacific States. Stanford Univ Press, Stanford, CA, 506 pp

Jameson EW Jr, Peeters HJ (1988) California mammals. California Natural History Guide 52, Univ Califrornia Press, Berkeley, 403 pp

Jefferies DJ, French MC (1976) Mercury, cadmium, zinc, copper and organochlorine insecticide levels in small mammals trapped in a wheat field. Environ Pollut 10:175–182

Josselyn M (1983) The ecology of San Francisco Bay tidal marshes: a community profile. US Fish Wildlife Serv, Div Biological Services, Washington, DC, FWS/OBS-83/23, 102 pp

Law LM, Goerlitz DF (1974) Selected chlorinated hydrocarbons in bottom material from streams tributary to San Francisco Bay. Pesticide Monitoring J 8:33–36

Long E, McDonald D, Matta MB, VanNess K, Buchman M, Harris H (1988) Status and trends in concentrations of contaminants and measures of biological stress in San Francisco Bay. NOAA Technical Memorandum NOS OMA 41, Seattle, WA 268 pp

Luoma SN, Cloern JE (1982) The impact of waste-water discharge on biological communities in San Francisco Bay, In: Kockelman WJ, Conomos TJ, Leviton AE (eds) San Francosco Bay: Use and protection, Sixty-first Annual Meeting Pacific Division, Am Assoc Advancement Sci, Univ California, Davis, Ca, pp 137–160

Moyer BR, Budinger TF (1974) Cadmium levels in the shoreline sediments of San Francisco Bay. In: Hemphill DD (ed) Trace substances in environmental health—VIII. Proc Univ Missouri's 8th Annual Conference on Trace Substances in Environmental Heath, Columbia, MO, pp 127–160

Nelson K, Baker RJ, Shellhammer HS, Chesser RK (1984) Test of alternative hypotheses concerning the origin of *Reithrodontomys raviventris:* genetic analysis. J Mamm 65:668–673

Neter J, Wasserman W (1974) Applied Linear Statistical Models, Richard D. Irwin, Homewood, Il, 842 pp

Ohlendorf HM (1989) Bioaccumulation and effects of selenium in wildlife. In: Jacobs LW (ed) Selenium in agriculture and the environment. Spec Publ 23, Soil Sci Soc Am, Madison, WI, pp 133–177

Ohlendorf HM, Fleming WJ (1988) Birds and environmental contaminants in San Francisco and Chesapeake Bays. Marine Pollut Bull 19:487–495

Ohlendorf HM, Marois KC (1990) Organochlorines and selenium in California night-heron and egret eggs. Environ Monit Assess 15:91–104

Ohlendorf HM, Custer TW, Lowe RW, Rigney M, Cromartie E (1988) Organochlorines and mercury in eggs of coastal terns and herons in California, USA. Colonial Waterbirds 11:85–94

O'Neil LJ (1988) Feasibility study of contamination remediation at Naval Weapons Station, Concord, California, Vol. II: Biological assessment. Misc. Paper EL–86–3. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS 50 pp + A1–15, B1, and C1–2.

Phillips DJH (1987) Toxic contaminants in the San Francisco Bay-Delta and their possible biological effects. Aquatic Habitat Institute, Richmond, CA, 413 pp

Shellhammer HS (1977) Of men and marshes. San Jose Studies, San Jose State Univ 3:23–35

——— (1982) Reithrodontomys raviventris. Mammalian Species. Amer Soc Mammalogists 169:1–3

——— (1989) Salt marsh harvest mice, urban development and rising sea levels. Conserv Biol 3:59–65

Shellhammer HS, Jackson R, Davilla W, Gilroy AM, Harvey HT, Simmons L (1982) Habitat preferences of salt marsh harvest mice (*Reithrodontomys raviventris*). Wasmann J Biol 40:102–114

Talmage SS, Walton BT (1991) Small mammals as monitors of environmental contaminants. Rev Environ Contam Toxicol 119:47–145

US Fish and Wildlife Service (1984) Salt marsh harvest mouse and California clapper rail recovery plan. US Fish Wildlife Serv, Portland, Oregon, 141 pp

Welch WR, Dick DL (1975) Lead concentrations in tissues of roadside mice. Environ Pollut 8:15–21

Zetterquist DK (1977) The salt marsh harvest mouse (*Reithrodontomys raviventris raviventris*) in marginal habitats. Wassmann J Biol 35:68–76

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