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BIOACCUMULATION OF METALS IN PLANTS, ARTHROPODS, AND MICE AT A SEASONAL WETLAND

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Abstract—Concentrations of arsenic, cadmium, copper, lead, and nickel were measured in soils, house mice (*Mus musculus*), and the main food items of this omnivorous mouse to examine the occurrence of these metals in selected components of a seasonal wetland. Soil concentrations of copper, lead, and (in some areas) nickel were elevated, but extractable soil concentrations indicated low bioavailability of metals. Levels of most metals in mice and composited arthropods were consistent with reference site concentrations from other studies. However, copper was found to be particularly mobile within the local ecosystem and accumulated in house mouse carcasses and composited arthropods at substantial levels. Metal residues in *Scirpus robustus* (alkali bulrush) roots exceeded those in seeds, consistent with patterns of bioaccumulation commonly observed in plants. Uptake and bioaccumulation factors for *S. robustus* seeds and roots, arthropods, and mouse carcasses and livers are reported. Concentrations of lead and nickel in *S. robustus* roots exhibited significant linear relationships with levels in soils. Copper levels in *S. robustus* seeds varied significantly with those in house mouse livers, suggesting that trophic transfer of copper from this food source to mice occurred. However, other spatial patterns of bioaccumulation in *S. robustus* and house mice relative to soil/seed concentrations were absent. Metal levels in house mice bore no relation to body weight or estimated age.

Keywords—Metal bioaccumulation Bioavailability Ecotoxicology Small mammals Terrestrial biota

INTRODUCTION

Concentrations of chemicals in soils and organisms provide information about their movement through the environment, bioaccumulation, trophic transfer, and potential toxicological effects. Many studies have examined the prevalence and distribution of trace metals in terrestrial food webs [1–5]. Patterns of uptake and bioaccumulation have been investigated by studying relationships between metal concentrations in soils and plants [6–8] and in soils and tissues of co-occurring animals [9,10]. A variety of physical and chemical soil characteristics mediate the release of metal species bound to clays, metal oxides, or organic matter in the soil [11], affecting uptake of metals by biota. These influences can complicate the identification of patterns of uptake and bioaccumulation.

The relative concentrations of metals among tissues of plants [12] or animals [1,13] can reveal general trends of exposure, uptake, translocation, and assimilation of metals within organisms. Trophic transfer of metals within the food web may be demonstrated by relating metal levels in dietary components with those assimilated by an animal. In addition, tissue residues in animals can indicate potential adverse effects posed by metals when linkages between toxicity test results and critical body residues are established [14].

This paper describes the occurrence and distribution of metals in selected components of a terrestrial food web at a seasonal wetland. Concentrations of arsenic, cadmium, copper, lead, and nickel were measured in soils and sediments, tissues of house mice (*Mus musculus*), and the mouse's principal food items. The study had five objectives: characterize the concentrations of these metals in soils and sediments, evaluate the bioavailability of metals in soils and sediments, interpret the magnitudes of metal accumulation in house mice and other biota, derive site-specific tissue:soil uptake and bioaccumulation factors for organisms at the site, and examine potential bioaccumulation and trophic transfer relationships through regressions of metal concentrations in organisms versus those in soils/sediments. Possible relationships between metal concentrations in house mice and their body weight or age were also examined.

METHODS

Site description

The study was performed at the former Mare Island Naval Shipyard on San Pablo Bay in Vallejo, California, USA. Ships and submarines were built, maintained, or repaired at the facility from the 19th century until the base was decommissioned in 1996. The 0.6-ha study site was within installation restoration site 1 (IR01), encompassing the northern portion of Wetland X [15]. This site consisted of a nontidal, seasonal, brackish wetland partially surrounded by disturbed nonnative grassland with scattered shrubs (Fig. 1). The site becomes partially inundated each year from late fall to early summer with seasonal rainwater and rising groundwater. During the summer and fall, the lowest-lying areas are barren salt pans. The wetland plant community is spatially heterogeneous mainly because of variations in microtopography and is dominated by *Salicornia virginica* (pickleweed), *Scirpus robustus* (alkali bulrush), *Atriplex patula* var. *hastata* (fat hen), and annual grasses. The most abundant small mammal at the site is the house mouse, which occurs year-round. California voles (*Microtus californicus*) are less abundant; they increase in numbers when green herbaceous vegetation is available but are nearly absent during dry months (K. Torres and M. Johnson,

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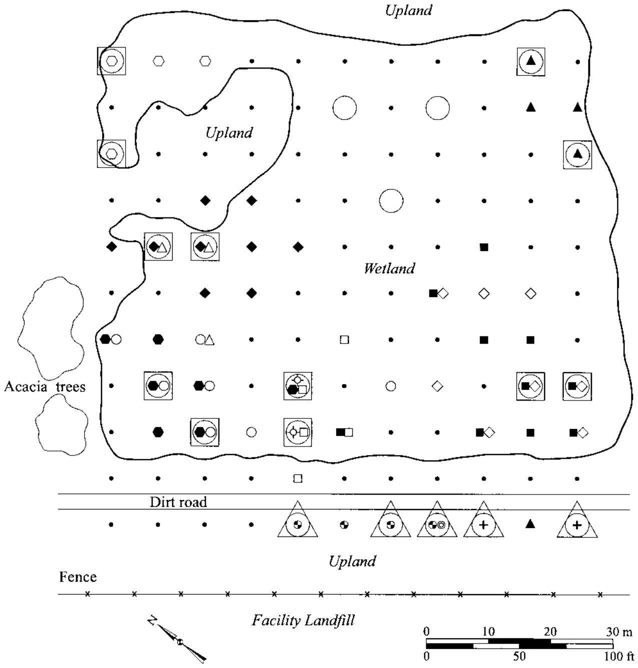

Fig. 1. Capture locations of sampled house mice and soil and plant sampling locations at study site, Mare Island, Vallejo, California, USA. ● Trap location; capture locations: ○ Mouse A, ◇ B, ◆ C, ■ D, ⬡ E, ◐ F, ⬢ G, ▲ H, △ I, ✜ J, □ K, ◎ L, and -◇- M; ◯ soil sample, □ *S. robustus* sample, △ *H. marinum* sample.

unpublished data). The federal and state endangered salt marsh harvest mouse (*Reithrodontomys raviventris*) was live-trapped only rarely during the study.

Potential sources of contaminants at or near the site include buried waste oil sumps; materials discarded at a former dumping ground (e.g., metal, concrete, and plastic construction debris); the adjacent facility landfill (active from 1965 to 1978); the historic landfill (utilized from 1942 to 1966) to the northwest; submarine batteries, which may have released lead oxide into the ground; and relatively high ambient levels of metals in the artificial fill that constitute much of the surface layer of Mare Island [15,16]. Past soil and sediment analyses at the site and in adjacent areas revealed the presence of elevated metals, polycyclic aromatic hydrocarbons, solvents, polychlorinated biphenyls, and petroleum hydrocarbons [16]. In the present study arsenic, cadmium, copper, lead, and nickel were evaluated because they were among the most elevated metals in soils and sediments [16] or exhibit potential for uptake and bioaccumulation.

Sample collection

Soils and sediments, plant materials, terrestrial arthropods, and mice were sampled from the study site for chemical analysis to evaluate aspects of metal bioaccumulation for each of the study objectives. Surface soils and sediments were not differentiated in sampling or data analysis and are hereafter referred to collectively as soils.

Small mammals were live-trapped from July to December 1997 in Sherman traps (Tallahassee, FL, USA) baited with wild birdseed. Traps were spaced at 25-ft (7.6-m) intervals within a 250- by 250-ft grid. Trapping was conducted during two-night periods occurring every other week, with 2 of the 11 periods consisting of four nights. Over a total of 3,146 trap-nights, 672 total captures were made of 199 individual house mice. During the fifth month of trapping, 11 mice identified as long-term residents of the site were sacrificed by carbon dioxide asphyxiation. Individuals were selected to maximize time since first capture, capture frequency, and discreteness of home range. Approximate home ranges of these mice were plotted on a map as capture locations (mean of 10.7 captures each) (Fig. 1). Two additional adults (L and M) that were trapped infrequently were also collected for analysis. All mice were weighed and frozen for subsequent dissection and chemical analysis.

Soil samples were apportioned so that home ranges of the 11 mice each contained two sampling locations and at least one location was assigned to capture locations of the other two mice (Fig. 1). The probability of each location sampled within a home range was weighted by the relative number of captures. To characterize other portions of the site, three soil samples were collected outside the capture locations. The collective area across sample locations was representative of those parts of the site utilized by the population at large, which excluded the more disturbed and barren areas. At each of 20 sampling locations, two soil samples were collected at random directions and distances, yielding a total of 40 sampling points. Soils were collected with a stainless-steel trowel from the surface to a depth of 6 in.

To determine which foods were consumed by house mice and consequently were potential pathways for trophic transfer of metals, dietary analyses were conducted on fecal samples from eight individuals trapped during the study. Feces were analyzed with microhistological techniques at Composition Analysis Laboratory (Fort Collins, CO, USA). Percentage relative densities of discernible food items were converted from frequencies of occurrence in microscope fields [17]. Relative densities were assumed to correspond to diet composition as percentage dry weight. Based on dietary data (see Results), seeds of the wetland plant *S. robustus* and arthropods were selected for chemical analysis. *Scirpus robustus* seeds, the primary food of local house mice, were present and collected from plants at 12 of the 20 sampling locations (Fig. 1). At eight of those locations, mature *S. robustus* roots were also sampled for chemical analysis to help evaluate the distribution of metals within the plant. Single composite samples of both seeds and roots were collected across the two soil sampling points at each location. In an upland area west of the dirt road containing no *S. robustus*, house mouse diets consisted primarily of grass seeds of the *Bromus* sp. type. For bioaccumulation modeling in Torres and Johnson [18], *Hordeum marinum* seeds were collected in a composite sample as a surrogate for all grass seeds in that area, as they were more available at the time of sampling (Fig. 1).

Individual arthropod taxa in house mouse diets were not identified through fecal analysis. Consequently, three of the most common and readily available species of terrestrial arthropods were sampled from the 20 locations. *Armadillidium vulgare* (pillbug, Isopoda) (n = 67 individuals), *Phidippus* sp. (jumping spider, Arachnida) (n = 29), and the web-spinning spider *Araneus* sp. (Arachnida) (n = 9) were collected with forceps from the ground or vegetation and frozen. Because of the limited amount of sample biomass, each arthropod taxon was analyzed as a single sitewide composite sample.

Chemical analysis

Soil samples were oven dried, ground, and analyzed at the University of California Division of Agriculture and Natural

Resources (DANR) Analytical Laboratory (Davis, CA, USA) for total metal content, partially extractable metal content, and several physical and chemical properties.

For each total metal analysis, a 0.5-g soil sample was combined with 0.5 ml of nitric acid and 2 ml of 30% hydrogen peroxide in a Teflon® PFA vessel. The mixture was microwaved for 14 min and diluted to 15 ml with deionized water. Soils analyzed for extractable metals were first processed with the diethylene triamine pentaacetic acid (DTPA) extraction method [19]. Analytical samples were prepared by adding 20 ml of 0.005 M DTPA extraction reagent to 10 g soil. The mixture was shaken for 2 h at 25°C and filtered. Totally digested and DTPA-treated soils were analyzed for arsenic, cadmium, lead, and nickel in a thermo Jarrell-Ash atom scan 25 inductively coupled plasma atomic emission spectrometer (ICP-AES; Franklin, MA, USA). Copper was measured with a Perkin-Elmer 2380 atomic absorption spectrometer (AAS; Norwalk, CT, USA). A method blank, duplicates, and National Institute of Standards and Technology (NIST) and in-house standard reference materials (SRMs) were analyzed for each metal. Recoveries from IRM 020 soil and IRM 012 ash (Ultra Scientific, North Kensingtown, RI, USA) and UCD 150 alfalfa (DANR Analytical Lab) SRMs were 94 to 100, 99, 94, 107, and 103% for arsenic, cadmium, copper, lead, and nickel, respectively.

To evaluate the potential bioavailability of metals from soils, four physical and chemical soil properties were determined: pH, cation exchange capacity, soil organic matter (calculated on the basis of an assumed 58% organic matter carbon content), and particle size (sand, silt, and clay content). One sample from each pair (20 of 40 samples) was analyzed for soil properties. One duplicate and one standard reference material were analyzed for each soil parameter, and a method blank was analyzed for percentage organic matter.

Mice were thawed, weighed, washed externally, and rinsed with deionized water. During dissection the liver was removed, weighed, and refrozen for separate analysis. The skin, pelage, feet, tail, and gastrointestinal tract were removed and discarded, and the carcass was homogenized with a Polytron tissue grinder (Brinkmann Instruments, Westbury, NY, USA) in a measured amount of double-deionized water. Seeds and *S. robustus* roots were air dried and cleaned of visible soil particles, and roots were rinsed and gently scrubbed with deionized water. Roots and seeds were ground to homogeneous powders. Each arthropod species was homogenized in a sitewide composite sample.

Plant, arthropod, and mouse tissues were analyzed for metals at the California Veterinary Diagnostic Laboratory System Toxicology Laboratory (Davis, CA, USA). Arthropod or mouse tissue was digested by combining 1 g homogenized tissue with 3 ml nitric acid; 0.5 g dried plant tissue was digested with 4 ml nitric acid. Samples analyzed for arsenic were amended with 1 ml perchloric acid and 1 ml sulfuric acid. Samples were digested in a Tecator digestion system (Hoganas, Sweden). Next, mixtures analyzed for arsenic were combined with 7 ml 5 M hydrochloric acid and 1 ml 10% potassium iodide solution; these samples were digested and diluted to 10 ml with deionized water. Digested samples analyzed for lead were also diluted with deionized water. To tissue samples analyzed for cadmium, copper, and nickel were added 2 or 5 ml hydrochloric acid; samples were diluted with deionized water.

Arsenic, cadmium, copper, and nickel were measured with ICP-AES on a Fison's Model Accuris ICP (Waltham, MA, USA). Arsenic was analyzed by hydride generation. Lead was measured with a Perkin-Elmer Model 5100 Zeeman-corrected atomic absorption spectrometer. The quality assurance/quality control measures included analysis of method blanks, duplicates, spike recoveries, and SRMs. The standard reference materials were NIST 1577b bovine liver (Gaithersburg, MD, USA), National Research Council of Canada (NRCC) TORT-2 lobster hepatopancreas (Ottawa, ON, Canada), NRCC DORM-2 dogfish muscle, and NRCC DOLT-2 dogfish liver. Recoveries from SRMs were 87 to 111, 96 to 103, 95 to 107, 82 to 103, and 87 to 112% for arsenic, cadmium, copper, lead, and nickel, respectively.

Mouse carcasses and arthropod composites were analyzed in duplicates where sufficient material was available. The spider *Phidippus* sp. was analyzed only for lead because of limited sample size. For data reporting, carcass results were adjusted on the basis of the amount of water added during homogenization. Copper levels in mouse livers were calculated into the separately measured carcass concentrations, but results for other metals were not combined in this way because they were undetected in carcasses and/or livers.

Uptake and bioaccumulation factors

Dry-weight, soil-to-plant uptake factors (PUFs) were calculated for *S. robustus* roots and seeds relative to soil concentrations and averaged across colocated samples. Soil-to-animal tissue bioaccumulation factors (BAFs) were calculated for arthropods and house mouse carcasses/livers on the basis of composited or average sitewide tissue concentrations, respectively. Measured wet-weight concentrations were converted to dry weight on the basis of assumed water contents of 65% in arthropods [20], 68% in small mammal whole bodies [20], and 72% in small mammal livers [21].

Bioaccumulation regressions

Scatter plots and regressions of *S. robustus,* mouse carcass, and liver concentrations on soil concentrations were created from colocated data (e.g., within home ranges of mice). To ascertain whether metals accumulated in house mouse tissues in proportion to age or body weight, carcass and liver concentrations were plotted against the estimated age and final body weight of each individual. The age of individual mice was estimated from body weight at first capture [22] increased by the time interval preceding final capture.

Data in each graph were fit to simple linear regression models using NCSS™ (Kaysville, UT, USA). Significance of linear relationships was evaluated with the t test (H_0: $B_1 = 0$). Data for metals without any detected residues were not analyzed. However, individual nondetects were included in graphs as one-half of the detection limits [23].

RESULTS

Metals in soils

Total concentrations of arsenic, cadmium, copper, lead, and nickel in soils and sediments (soils) are shown in Table 1. Levels of copper and lead were the most variable across the site, as indicated by the wide confidence intervals of the means. Arsenic, cadmium, and nickel were distributed more homogeneously in soils (Table 1).

Physical and chemical characteristics of soils varied relatively little across the site despite marked differences in microtopography, inundation, and vegetation types (Table 2). Soils were characterized by a neutral pH (mean of 7.1), low

Table 1. Metal concentrations (total and extractable) in soils (mg/kg dry wt)

	Arsenic[a]	Cadmium	Copper	Lead	Nickel
Total	10 ± 0.9 (4–15) (40)	1.8 ± 0.1 (1.4–2.2) (40)	236 ± 94 (70–1,510) (40)	107 ± 26 (38–413) (40)	122 ± 7 (90–219) (40)
DTPA extractable[b]	1 ± 0.0 (ND − 1)[c] (40)	0.4 ± 0.04 (0.2–0.7) (40)	55 ± 19 (13–247) (40)	14.7 ± 2.7 (3.7–43.4) (40)	5.6 ± 0.8 (3.2–17.6) (40)
Percentage extractable (%)	9.9 ± 1.3 (6.7–20.0) (40)	23.1 ± 1.9 (13.3–31.8) (40)	24.3 ± 2.0 (8.8–39.0) (40)	14.5 ± 1.2 (8.3–22.4) (40)	4.5 ± 0.4 (2.8–9.4) (40)
Mare Island artificial fill[d]	36	5.2	120	59	130
Probable effects level[e]	17	3.53	197	91.3	35.9

[a] Reported values are for detects only, mean ± 95% confidence interval, $p \leq 0.05$. Ranges in parentheses above. Sample sizes in parentheses below.
[b] DTPA = diethylene triamine pentaacetic acid.
[c] ND = not detected in 18 samples (detection limit = 1 mg/kg).
[d] 95th-percentile ambient concentration [48].
[e] Freshwater sediment [49].

organic matter and sand content, and a relatively high cation exchange capacity and silt and clay contents. The DTPA-extractable concentrations of metals and the percentages of total metal concentrations extractable by DTPA suggest limited potential for release of bound metals in soils; extractable metals ranged from 4.5% for nickel to 24.3% for copper (Table 1).

Diet composition of house mice

Analysis of fecal samples collected from house mice revealed a total of nine discernible dietary components. *Scirpus robustus* seeds and arthropod parts (not identified to taxa) were the two most abundant components (relative densities of 74.0 and 8.9%, respectively). Other plants (*Salicornia virginica*, *Bromus* sp. type, *Evolvulus* sp., and two unidentified plants) collectively totaled 17.1% of the house mouse diet. *Setaria italica* (millet) seeds used in trap bait averaged 17.7% of the relative density of identified fecal materials. Relative densities of other dietary items were retabulated excluding *S. italica* seeds for bioaccumulation modeling [18].

Metals in organisms

In *S. robustus* metals accumulated at substantially higher levels in roots than in seeds (Table 3). Copper exhibited the highest root concentrations, averaging 287 mg/kg. Seed concentrations were also highest for copper, followed by nickel; the remaining metals were present at much lower or undetected levels in seeds. Copper and nickel also showed the highest seed:root concentration ratios in *S. robustus* (Table 3). Lead was measured at 0.376 mg/kg in composited *H. marinum* seeds.

The sitewide composite of the detritivorous isopod *A. vulgare* contained higher concentrations of all metals than did the composited spider *Araneus* sp. (Table 3). In both species, copper levels were highest, while lead and arsenic were among the least accumulated metals. The composited spiders *Araneus* sp. and *Phidippus* sp. contained similar levels of lead.

Among the metals detected in house mouse carcasses, copper occurred at the highest levels, followed by lead, with arsenic found at the lowest levels (Table 3). Cadmium and nickel were undetected in all carcasses. Copper, which was the only metal detected in livers, was measured at lower concentrations in livers than in carcasses.

Uptake and bioaccumulation factors

Both PUFs and BAFs summarize the bioaccumulation of metals in specific biota and tissues relative to soil levels (Table 4). The largest *S. robustus* root:soil PUFs were calculated for cadmium (3.5), arsenic (1.7), and copper (1.1); lead and nickel had PUFs lower than 1. The *S. robustus* seed:soil PUFs for copper and nickel were higher than those for arsenic and lead.

Armadillidium vulgare:soil BAFs derived from individuals composited across the site indicate that copper (5.6) and cadmium (2.7) accumulated more than arsenic (0.12), nickel (0.07), and lead (0.04) relative to ambient soil levels. A similar pattern held for cadmium (2.2), copper (0.82), arsenic (0.09), nickel (0.02), and lead (0.01) in *Araneus* sp.

In house mouse carcasses, copper accumulated at the highest levels with respect to soil concentrations; on a dry-weight basis, copper was present in carcasses at half of the mean soil concentration (Table 4). Copper accumulated in livers at less than six times the accumulation in carcasses relative to soil concentrations. Liver:soil BAFs for other metals were not quantified because of undetected residues in livers.

Table 2. Soil characteristics

	pH[a]	CEC (meq/100g)[b]	Organic matter (%)	Particle size (%) Sand	Silt	Clay
Value	7.1 ± 0.1 (6.5–7.7) (20)	39.5 ± 1.3 (31.5–42.5) (20)	2.8 ± 0.2 (1.9–3.8) (20)	12 ± 3 (6–26) (20)	45 ± 2 (36–50) (20)	43 ± 2 (35–52) (20)

[a] Values are mean ± 95% confidence interval ($p \leq 0.05$). Ranges in parentheses above. Sample sizes in parentheses below.
[b] CEC = cation exchange capacity.

Bioaccumulation and trophic transfer relationships

A statistically significant relationship was observed between lead concentrations in *S. robustus* roots (ln transformed to meet the assumption of constant error variance) and total lead concentrations in soil ($r^2 = 0.59$; Fig. 2a). A similar relationship between nickel levels in roots and total nickel levels in soil was also found ($r^2 = 0.68$; Fig. 2b). No such patterns between root and total soil levels of other metals existed. When concentrations in *S. robustus* roots were plotted against DTPA-extractable soil concentrations, no significant relationships held for cadmium, copper, or nickel. Lead levels in *S. robustus* roots, however, varied significantly with DTPA-extractable soil concentrations ($r^2 = 0.79$; Fig. 3). Root concentrations of lead were ln transformed to meet the assumption of constant error variance. No significant relationships were observed between metal concentrations in *S. robustus* seeds and total soil, extractable soil, or root concentrations.

Concentrations of metals in house mouse carcasses exhibited no significant relationships with total soil, extractable soil, or *S. robustus* seed concentrations averaged over individual home ranges, nor were relationships found between carcass concentrations of metals and either final body weights or estimated ages of mice.

Since most metals were undetected in livers, only regressions with copper were modeled. No statistical trend was observed between copper levels in livers and in soil (total or extractable concentrations) or with body weights or estimated ages. However, liver concentrations of copper did vary significantly with copper concentrations in seeds averaged over the home ranges of individuals ($r^2 = 0.51$; Fig. 4). Liver concentrations were square-root transformed to meet the assumption of constant error variance.

DISCUSSION

Concentrations and bioavailability of metals in soils

Concentrations of arsenic and cadmium in surface soils and sediments (soils) were within ambient concentrations in Mare Island artificial fill, which generally originated from dredged offshore sediments, and probable effects levels for freshwater sediments (Table 1). However, concentrations of copper, lead, and (in some areas of the wetland) nickel were clearly elevated above these values (Table 1). Identifying the origins of metals in sediments and upland soils at the site is complicated by the various contributions from the island's bay sediment substrate and on-site and off-site activities.

While high concentrations of copper, lead, and nickel pose potentially high exposures to local biota, conditions mediating bioavailability also must be considered in characterizing the transfer of metals into the food web. Relatively small fractions of total metals in soil were extractable with DTPA (Table 1), indicating limited availability of metals for uptake by organisms. Use of DTPA soil extraction as an indicator of metal availability to plants has been demonstrated for zinc, copper, manganese, and iron [19] and also exhibits potential for use with cadmium, lead, and nickel [24,25]. However, the suitability of using the DTPA test to estimate arsenic bioavailability is questionable [26].

Metal uptake and bioaccumulation

Scirpus robustus exhibited substantial enrichment of metals in roots relative to those in seeds (Table 3). This pattern is in agreement with the observed tendency of many metals to become immobilized in root and other below-ground storage tissues and undergo limited translocation to aboveground structures [27,28]. Seed:root concentration ratios were relatively low for all metals (Table 3), consistent with findings that seeds typically contain much lower concentrations of heavy metals than other plant parts [12].

As for differences among metals, concentrations in roots and seeds were highest for copper, which was the metal also present at the greatest soil concentrations. The metal with the highest root:soil PUF was cadmium, with nickel and lead exhibiting the lowest accumulation in roots relative to ambient soil concentrations (Table 4). This finding was consistent with the greater soil bioavailability and root uptake observed for cadmium compared to most other heavy metals [3,28]. The lower root:soil PUF for lead (Table 4) was in agreement with the limited uptake of lead by roots [12,27]. Lead accumulation in roots is commonly overestimated since much of the lead measured in roots is bound tightly on surface deposits and is not biologically assimilated [8,29]. Copper levels in *S. robustus* seeds were clearly greater than levels of other metals in seeds, followed by nickel (Table 3). This is consistent with findings that copper and nickel accumulate to a greater extent than cadmium and lead in grains of wheats and oats [12,30].

By their trophic status the terrestrial arthropods (a detritivorous isopod and two carnivorous arachnids) are expected to have greater potential for metal accumulation than most other invertebrates occurring in the area. Concentrations of copper, lead, and nickel in composite samples of the isopod *A. vulgare* exceeded those in the two spiders (Table 3). Terrestrial isopods accumulate metals to a high degree as decomposers in intimate contact with soil and plant litter and have been promoted as biomonitors for this reason [4].

Concentrations of cadmium in *A. vulgare* and the spider *Araneus* sp. and levels of lead in *A. vulgare, Araneus* sp., and *Phidippus* sp. (Table 3) were similar to concentrations found in other terrestrial isopods and spiders from unpolluted habitats (Table 5). The cadmium BAFs calculated for *A. vulgare* and *Araneus* sp. were lower than BAFs reported for other isopods and spiders (means of 21.1 and 18.2, respectively) (converted to dry weight assuming 65% water content in arthropods) [31]. However, copper concentrations in *A. vulgare* and *Araneus* sp. were high relative to reference concentrations (Table 5)

Table 3. Metal concentrations in *Scirpus robustus*, arthropods, and house mice (mg/kg)

Organism/tissue	Arsenic[a]	Cadmium	Copper	Lead	Nickel
Plants					
S. robustus roots[b]	18.1 ± 5.9 (7.91–29.1) (8)	6.7 ± 1.1 (4.9–9.2) (8)	287 ± 138 (84.6–600) (8)	64.5 ± 39.1 (21.0–168) (8)	29.4 ± 7.9 (21.0–50.8) (8)
S. robustus seeds[b]	0.030 ± 0.010 (0.015–0.064) (11)	ND[c] (12)	12.7 ± 1.2 (9.8–16.3) (12)	0.107 ± 0.049 (ND − 0.160)[d] (12)	1.6 ± 0.2 (ND − 1.9)[e] (11)
Ratio of seed:root concentrations	0.002 ± 0.001 (0.001–0.004) (7)	<0.11 (8)	0.06 ± 0.03 (0.02–0.13) (8)	0.002 ± 0.007 (0.001–0.005) (3)	0.05 ± 0.02 (0.02–0.06) (4)
Arthropods[f,g]					
Armadillidium vulgare	0.419	1.7	462	1.39	2.8
Phidippus sp.	—	—	—	0.303	—
Araneus sp.	0.308	1.4	67.7	0.193	0.7[h]
House mice[f]					
Carcasses	0.030 ± 0.022 (ND − 0.129)[i] (13)	ND[j] (13)	40.1 ± 25.3 (6.4–164) (13)	1.98 ± 1.05 (0.216–5.18) (13)	ND[j] (13)
Livers	ND[k] (13)	ND[l] (13)	5.4 ± 0.9 (3.9–8.9) (13)	ND[k] (13)	ND[l] (13)

[a] Reported values are for detects only (mean ± 95% confidence interval, $p \leq 0.05$). Ranges in parentheses above. Sample size in parentheses below.
[b] Dry weight.
[c] ND = not detected (detection limit = 0.7 mg/kg).
[d] ND = not detected in seven samples (detection limit = 0.029 mg/kg).
[e] ND = not detected in five samples (detection limit = 0.7 mg/kg).
[f] Wet weight.
[g] Reported values are for single sitewide composites.
[h] ND = not detected in the paired subsample (detection limit = 0.3 mg/kg).
[i] ND = not detected in two samples (detection limits = 0.010 and 0.024 mg/kg).
[j] ND = not detected (detection limits = 0.4–0.7 mg/kg).
[k] ND = not detected (detection limit = 1 mg/kg).
[l] ND = not detected (detection limit = 0.3 mg/kg).

Table 4. Plant and animal bioaccumulation factors

Organism/ tissue:soil	Plant uptake factor/bioaccumulation factor[a]				
	Arsenic	Cadmium	Copper	Lead	Nickel
Scirpus robustus					
Root:soil	1.7	3.5	1.1	0.42	0.24
Seed:soil	0.003	<0.38[b]	0.06	0.001	0.01
House mouse					
Carcass:soil	0.01	<1.0[b]	0.53	0.06	<0.02[b]
Liver:soil	<0.36[b]	<0.59[b]	0.08	<0.03[b]	<0.01[b]

[a] Calculated from detected values only unless otherwise specified.
[b] Undetected in tissue; upper limit of PUF/BAF based on average detection limits.

and similar to those in isopods and spiders from copper-polluted sites [4,32]. Measured levels of arsenic and nickel in these taxa do not appear elevated.

Carcasses of house mice contained concentrations of arsenic, lead, and nickel that were within the ranges of average whole-body or carcass concentrations observed in rodents from reference sites or other areas with low metal pollution (Table 5). Lead concentrations in carcasses were far below whole-body concentrations (41 and 44 mg/kg wet wt) associated with kidney pathology in short-tailed voles (*Microtus agrestis*) [21]. Arsenic and lead concentrations in carcasses may be at least slightly underreported since carcass concentrations could not be adjusted with undetected residues of these metals in livers. Carcass concentrations of lead should not be significantly biased since more than 90% of the total mammalian body burden of lead is stored in bone (P. Barry, 1975, as reported in [33]). Excluding hair and nails from carcass analyses was likely to result in lower arsenic concentrations in carcasses compared to whole-body concentrations since much of the arsenic in mammals is stored in hair and nails. Cadmium and nickel were undetected in all house mouse carcasses, but, on the basis of its detection limits (0.4–0.7 mg/kg), nickel also appeared to be within ambient levels in rodents (Table 5).

Copper concentrations in house mouse carcasses (arith-

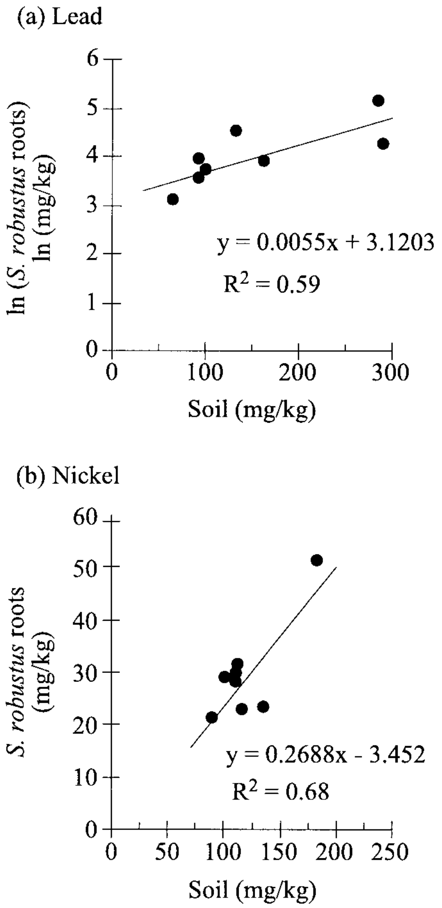

Fig. 2. Plotted relationships between concentrations of (**a**) lead and (**b**) nickel in *Scirpus robustus* roots and in totally digested soils. Significant relationships based on *t* test for $B_1 = 0$: (**a**) $t = 2.9343$, 6 degrees of freedom, $p = 0.0261$; (**b**) $t = 3.5488$, 6 degrees of freedom, $p = 0.0121$.

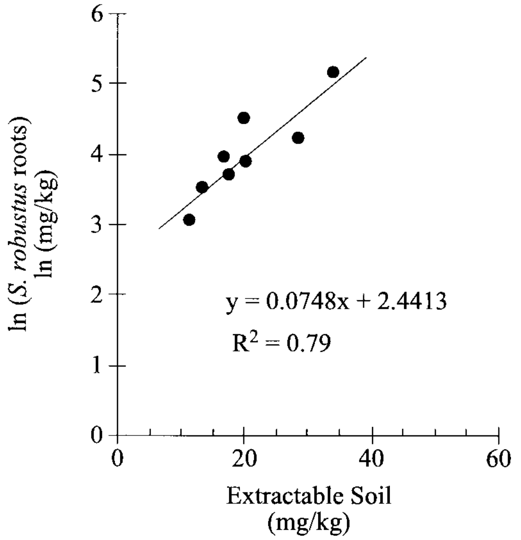

Fig. 3. Plotted relationship between concentrations of lead in *Scirpus robustus* roots and in diethylene triamine pentaacetic acid-extractable soil. Significant relationship based on *t* test for $B_1 = 0$: $t = 4.7659$, 6 degrees of freedom, $p = 0.0031$.

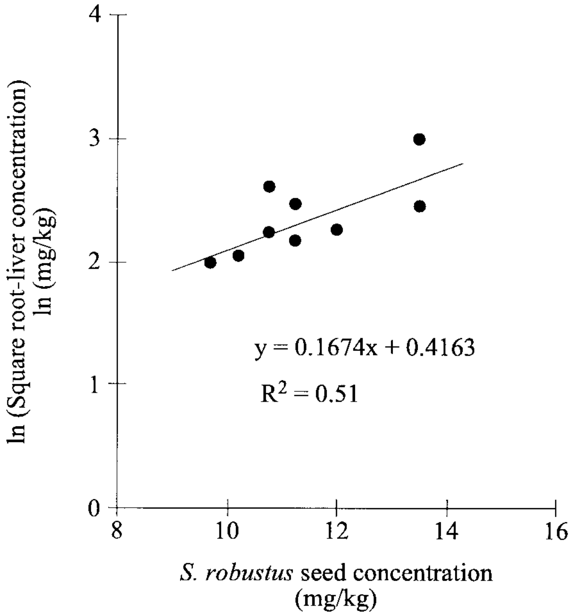

Fig. 4. Plotted relationship between square-root copper concentrations in house mouse livers and concentrations in *Scirpus robustus* seeds in individual home ranges. Significant relationship based on *t* test for $B_1 = 0$: $t = 2.7216$, 7 degrees of freedom, $p = 0.0297$.

Table 5. Average metal concentrations reported in arthropods and rodents from unpolluted reference sites[a]

	Concentration (mg/kg wet weight)[b]				
	Arsenic	Cadmium	Copper	Lead	Nickel
Arthropods					
Terrestrial isopods	—	2.1–12.7	9.1–85	0.3–13.2	—
Spiders	—	0.1–1.0	14.8–49	0.5–2.8	—
Rodents					
Whole body/carcass	0.004–0.04	0.02–0.3	2.1–4.3	0.2–2.7	0.36–3.1
Liver	0.06–2.6	0.03–0.3	2.6–23.3	0.1–2.5	0.5–1.2

[a] Sources: Hunter et al. [4]; Talmage and Walton [21]; Hopkin [32]; Eisler [39]; others cited in Torres [50].
[b] Dry-weight concentrations were converted to wet-weight values assuming moisture contents of 65% in arthropods [20] and 68% and 72% in whole bodies and livers, respectively, of small mammals [20, 21].

metic mean 40.1 mg/kg; geometric mean 27.6 mg/kg) were considerably greater than those reported in rodents from both reference sites (Table 5) and sites with identified copper pollution (body burdens ranging up to 26.3 mg/kg wet wt) [5,21,34]. A very high body burden of copper (522 mg/kg wet wt) was also noted in one house mouse collected elsewhere on Mare Island [15]. Although copper was found at high levels in soil and arthropods at the site, it seems evident that the substantial levels of copper in house mice could not occur without disruption of internal copper regulation. Gastrointestinal absorption of copper in mammals is normally regulated by the amount of copper in the gastrointestinal tract [35]. Storage and biliary excretion of copper as coordinated by the liver is actively regulated by blood copper levels and hormones [36]. Copper accumulation in mammals also can be influenced by genetic factors and dietary levels of proteins, cadmium, silver, zinc, iron, and molybdenum [36,37]. Reports of no significant differences in body burdens of copper in small mammals among polluted and unpolluted sites have been attributed to effective homeostatic control of this essential metal [5,21]. However, differences in the concentration of copper in livers noted among sites with varying contamination suggest that internal copper regulation may prove ineffective for animals inhabiting highly polluted areas, possibly the case for mice at this site [1,13].

Undetected levels of arsenic, cadmium, lead, and nickel and measured levels of copper in house mouse livers were consistent with background concentrations in rodent livers (Table 5). Lead accumulated in livers below the toxic range for mammals (above 1.4 mg/kg wet wt [33]), and cadmium levels were far below those linked to liver pathology in common shrews (*Sorex araneus*) at a smelter site (84 to 280 mg/kg [38]). It is uncertain why copper was markedly elevated in carcasses (including liver concentrations) but not in livers. These results are at odds with observations that copper preferentially accumulates in liver compared with muscle, bone, and other tissues [1].

Copper was the only metal examined that was found at excessive levels in house mice relative to literature values. In healthy mammals exposed to copper, barriers to copper absorption and incorporation of copper ions into hepatic metallothionein, nuclear proteins, and lysosomes generally protect against copper toxicity except at very high exposures [36,39]. At high oral exposures, liver and kidney damage, anemia, retarded growth, reproductive and developmental effects, and mortality may occur [35,39]. It is unknown whether house mice in this study were adversely affected by ingested copper. Population data collected during trapping indicated that the density of house mice varied from 49 to 105 individuals/ha, with the population increasing at the close of the study (K. Torres and M. Johnson, unpublished data).

A previous investigation of small mammals at Mare Island and other pickleweed marshes along San Francisco and San Pablo Bays (CA, USA) found variable levels of metals and detectable levels of polychlorinated biphenyls in tissues but was unable to conclude whether contaminants posed harmful effects to species such as the endangered salt marsh harvest mouse [40]. Possible risks to salt marsh harvest mice in Mare Island wetlands at and near the study site were identified for lead, nickel, manganese, and selenium using conservative assumptions [15]. Additional research on the local diet of this mouse would help in quantifying its chemical exposures in potentially contaminated wetlands.

In terrestrial ecological risk assessments, increased data on tissue residues would eliminate problems associated with bioavailability assumptions in assessing soil contamination and reduce uncertainties in exposure modeling. Critical whole-body and organ residues associated with acute or chronic effects have been established for certain metals and organic compounds in aquatic organisms [14,41], but data for terrestrial wildlife are lacking. Efforts to quantitatively link tissue residues, physiological biomarkers, histopathology, and relevant effects in wildlife species exposed in the laboratory [42], in experimental field enclosures [43], and at contaminated sites [44] are valuable. These data are critical in view of the complexities of interspecies and seasonal exposure shifts, metal speciation, metallothionein binding and regulation, and dose-dependent mechanisms of toxic action.

Bioaccumulation and trophic transfer relationships

The most direct bioaccumulation pattern examined, that between metal concentrations in *S. robustus* roots and in ambient soils (uptake), exhibited significant linear relationships for lead and nickel (Figs. 2 and 3). Indeed, metal concentrations in soils are the primary factor determining concentrations in rooted aquatic macrophytes, despite the intimate contact of submerged plants with the water column [45]. However, levels of the other three metals in roots did not vary significantly with either total or extractable soil concentrations. Other studies failed to show positive relationships between levels of arsenic, cadmium, or lead in roots of estuarine and aquatic plants and those in soils or sediments [7,8], and arsenic levels in the roots of one plant were negatively correlated with soil levels [7].

No statistically significant relationships existed between metal concentrations in *S. robustus* seeds and in roots. The correspondence between seed and root levels would depend on metal translocation from roots to seeds, a transport and storage process not necessarily directly dependent on root concentrations. The lack of a trend between *S. robustus* seed and soil concentrations is not surprising, given the added factors of soil availability and root uptake.

Tissue burdens of metals in terrestrial animals may vary with ambient soil concentrations through direct ingestion of soil particles and via transfer through the food web. Metal bioaccumulation in house mouse carcasses and livers was not significantly related to soil concentrations in the home ranges of individual mice. In contrast, Shore [10] found significant correlations between liver and kidney levels of cadmium in field mice (*Apodemus sylvaticus*) and common shrews and levels of these metals in associated soils, and between liver and kidney concentrations of lead in field mice and short-tailed voles and concentrations in soils. Sharma and Shupe [9] also reported a significant relationship between cadmium levels in rock squirrel (*Spermophilus variegatus*) livers and soil but uncovered no such patterns for arsenic or lead.

The significant relationship between copper concentrations in livers and *S. robustus* seeds (Fig. 4) indicates that trophic transfer of copper to house mice most probably occurred. Similarly, in a study of metal accumulation in forest plants and animals, copper concentrations in wood mouse (*Apodemus flavicollis*) livers were positively correlated with concentrations in the species' main dietary item (*Fagus sylvatica* nuts) [46]. However, the present study did not demonstrate any trends of concentrations of copper or other metals in carcasses with increasing *S. robustus* seed concentrations. A possible explanation is that copper accumulates in brain, muscle, and bone (which constitute a large portion of the carcass biomass) less closely in relation to environmental contamination than it does in liver, kidneys, or hair [1].

Finally, the absence of relationships between house mouse tissue concentrations and estimated age or body weight did not support other findings that these time-varying factors are associated with metal accumulation. Cadmium is known to accrue with age in kidneys and liver, but cadmium concentrations could not be regressed on age or body weight because of lack of detection in livers and carcasses. Lead similarly accumulates in bone over time, but no such pattern was seen in carcasses.

In general, the lack of regression relationships involving metal accumulation in biota may be due to effective regulation of metals by organisms and/or spatial variation in availability of metals from soil or food. Extractable metal concentrations were applied as indicators of bioavailable fractions in the soil, but soil characteristics were not considered in regression models. While some studies (e.g., [47]) have found significant relationships through multiple regressions among metal concentrations in plants and various extractable soil or sediment fractions, others (e.g., [6]) have had limited or no success relating plant concentrations to soil properties through simple or multiple regression models.

SUMMARY

Soil and sediment concentrations of copper, lead, and (in some areas) nickel were elevated relative to ambient fill concentrations and sediment criteria. Extractable concentrations in soil suggested that the potential for metal bioavailability was low, and levels of most metals measured in mouse tissues and composited arthropods were generally consistent with available reference site concentrations from other studies. However, copper was found to be particularly mobile within the local ecosystem and accumulated in house mouse carcasses and composited arthropods at substantial levels. Metal residues in *S. robustus* roots exceeded those in seeds, consistent with patterns of bioaccumulation and translocation commonly observed in plants. Concentrations of lead and nickel in *S. robustus* roots exhibited significant correlations with levels in ambient soils. Copper levels in *S. robustus* seeds varied significantly with those in house mouse livers, suggesting that trophic transfer of copper from this food source to house mice occurred. However, other spatial patterns of bioaccumulation in *S. robustus* with respect to soil levels and in house mice relative to soil and seed concentrations were not demonstrated. Finally, metal levels in house mice bore no relation to body weight or estimated age.

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