THE CESIUM-POTASSIUM RATIO AND TRACE METAL BIOMAGNIFICATION IN TWO CONTAMINATED MARINE FOOD WEBS

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ABSTRACT

Muscle tissue concentration ratios of cesium (Cs) to potassium (K) appear to be useful indicators of the biomagnification potential of marine food webs. Application of this technique indicated that two metals-rich ecosystems in southern California, the Salton Sea and the municipal wastewater discharge zone off Palos Verdes Peninsula, are sufficiently "structured" to permit food web magnification. Despite this, with the possible exception of mercury no significant biomagnification of the contaminant trace metals was observed.

1. INTRODUCTION

The rapidly growing utilization of the ocean's resources has led to increasing concern about resultant damage to marine ecosystems. Activities such as the estuarine and coastal discharge of urban runoff and municipal wastewater, ocean dumping of domestic and industrial sludges, dredging of contaminated harbor sediments, and marine discharge of drilling fluids and cuttings can cause distinct elevations in levels of a wide variety of potentially toxic substances in the receiving water ecosystem. One major concern is that these toxic substances will be accumulated by organisms at the base of the food web, and then successively concentrated at higher feeding or trophic levels until damaging body burdens are reached. In this paper we will describe a technique of measuring the potential for such biomagnification in marine and estuarine ecosystems; then we will examine the extent to which one class of contaminants, the toxic trace metals, are biomagnified up two different types of marine food webs.

2. BACKGROUND

The Cs/K Ratio

A "structured" food web has been defined by Isaacs (1) as one composed of species with distinct feeding relationships that can cause successively increased concentrations of some pollutants. Young (2) investigated the distribution of a major radioactive fallout constituent, cesium-137, in the quasi-marine ecosystem of the Salton Sea in southern California. This well-mixed saline lake supported a population of transplanted marine and euryhaline organisms which had been shown to occupy distinct trophic level positions. Young found that cesium-137 concentrations, and the ratio of cesium-137 to potassium (a well-regulated essential electrolyte) in muscle tissue of the major marine fishes living there increased two to three fold per trophic level step. This observation generally was consistent with those made earlier in terrestrial and freshwater ecosystems. In addition, Young showed that the ratio of stable cesium (Cs) to potassium (K) in the Salton Sea ecosystem also increased by a factor of two to three per trophic level step. Under equilibrium conditions, such increases in Cs/K ratios over known food chain links or trophic level steps can be expected because Cs has been found to have a biological half-life that is generally two to three times that of the well-regulated K (2,3).

These results suggested that Cs/K ratios are useful chemical indicators of a given ecosystem's potential for biomagnification of pollutants (or other substances) with sufficiently long biological half-lifes. Pendleton et al. (4) defined the term "increase ratio" as follows:

$$\frac{\text{Body or Tissue Cs/K}}{\text{Diet Cs/K}}$$

Here we will alter this concept to include the ratio of any given parameter C (such as Cs/K or a tissue metal concentration) in organisms occupying trophic levels j+1 and j, respectively:

$$\frac{(C)_{j+1}}{(C)_j}$$

We call this ratio the "trophic step increase factor".

Thus, under the assumptions stated above, in a highly-structured marine ecosystem the average Cs/K increase factor should fall between 2 and 3.

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Substantially lower values than 2 would indicate a significant degree of "mixing" between the presumed trophic levels, such as would occur if the food web sampled actually contained a significant percentage of omnivores (multi-directional feeders). The greater the degree of such mixing (i.e., the closer the average Cs/K increase factor approaches 1.0), the less the potential for food chain magnification of biologically-persistent pollutants.

Target Ecosystems

For this discussion two different types of contaminated marine food webs were selected. The first was composed of fishes living in the Salton Sea during 1978, eleven years after Young's original chemical investigation. Drainage from the intense agriculture of the region has resulted in concentrations of dissolved trace metals in the Sea which equal or exceed those measured in several of southern California's major harbors (unpublished data). This drainage also has provided a high nutrient content in the Sea which supports dense populations of phytoplankton and phytoplankton-feeding zooplankton (assigned trophic levels I and II, respectively). The resultant detrital layer (trophic level I-II) is fed upon by a nereid worm (Neanthes succinea), which therefore is assigned a tropic level of II-III. This is the major food of two forage fishes, sargo (Anisotremus davidsoni) and gulf croaker (Bairdiella icistia), which thus are assigned trophic levels of III-IV. In the 1950's and 1960's croaker was the principal food of the orangemouth corvina (Cynoscion xanthulus), which therefore was assigned a trophic level of IV-V. However, in recent years two euryhaline fishes, the sailfin molly (Poecilia latipinna) and a tilapia (Tilapia sp.), have migrated from the adjacent freshwater canals and established larger populations in the Sea. These fishes apparently feed principally on algae and detritus; thus, we assign them trophic levels II-III. Another migrant from the canals, the thread fin shad (Dorosoma petenese), feeds principally on zooplankton and therefore is assigned to trophic level III. In recent years, tilapia has become an important food of the corvina. Assuming that croaker (III-IV) and tilapia (II-III) were of approximately equal importance to the corvina sampled in 1978, we tentatively have re-assigned that predaceous fish an average trophic level of IV.

The second food web sampled was composed of bottom dwelling and/or feeding seafood invertebrates and fishes commonly collected from the municipal wastewater discharge zone of Los Angeles County Sanitation District. This zone is located off Palos Verdes Peninsula on the southern California coast. The bottom sediments in this zone have been highly contaminated by toxic trace elements and chlorinated hydrocarbons carried in the wastewater released by the Joint Water Pollution Control Plant (JWPCP) to the nearshore marine ecosystem (5). The benthic community in this region has been intensively studied by marine biologists for many years. Based on the feeding habits information obtained from such studies, we have estimated the probable trophic level positions of the organisms sampled.

In an effort to seek correlations between such positions and tissue concentrations, we have converted these estimated positions to numerical trophic level assignments (TLA) with a resolution of 0.25 units. For example, if an organism falls between Trophic Levels III and IV, but appears to be closer to Level IV, it is given a TLA of 3.75 (6).

The following TLAs were given to the seafood organisms included in this study. The black abalone (Haliotis cracherodii), which feeds principally on algae (I), has a TLA of 2.0. The purple-hinged rock scallop (Hinnites giganteus) feeds on phytoplankton (I) and detritus (I-II) and is given a TLA of 2.25. The California spiny lobster (Panulirus interruptus) feeds on invertebrates such as sea urchins (II) and is given a TLA of 3.0. The ridgeback prawn (Sicyonia ingentis) feeds on invertebrates such as ostracods, which appear to be somewhat higher in the food web (II-III); thus the TLA is 3.5. (The prawn samples were collected outside the target area shown in Figure 1; thus, only their Cs/K ratios are considered here.) The diet of the yellow crab (Cancer anthonyi) is quite varied, including small invertebrates (II) and fishes (III); thus, its TLA is 3.5. The Pacific sanddab (Citharichthys sordidus) and white croaker (Genyonemus lineatus) feed on benthic and epibenthic crustaceans (II-III), and small fishes (III), and are given a TLA of 3.75. The California halibut (Paralichthys californicus), which feeds largely on anchovy (III) and benthic invertebrates and fish (III-IV), receives a TLA of 4.25. Finally, California scorpion fish (Scorpaena guttata) and Bocaccio (Sebastes paucispinis) feed on various fishes, crustaceans, and mollusks occupying levels III-IV, and thus are given TLAs of 4.5.

3. PROCEDURES

The Salton Sea samples were collected by gill net and seine during March 1978 from the northern (North Shore) region of the Sea. The coastal sea food samples were collected by various fishing techniques during 1975-1977 from the JWPCP discharge monitoring zone. (The scallop samples included both 1974 and 1976 collections.) Virtually all samples discussed here were obtained from within an area approximately 6 km by 3 km around the outfall diffuser system, in the region of highest sediment contamination. Corresponding samples also were collected from island or coastal control sites. All specimens were wrapped in clean plastic bags and frozen. Subsequently, samples of muscle tissue were dissected from the specimens while in a semi-thawed condition, using frequently cleaned carbon steel scalpels with plastic handles, and a coring technique designed to avoid introducing contamination to the tissue sample from the specimen exterior during dissection. In most cases, three specimens of each species from both the outfall and control site were analyzed individually. The samples then were digested in fuming nitric acid and analyzed by atomic absorption spectrometry (AAS); mercury was analyzed by cold vapor AAS.

4. RESULTS

In Figure 1, median values for the Cs/K ratio and median concentrations of eight trace metals in muscle tissue of the 1978 Salton Sea specimens are compared to the estimated trophic level occupied by a given species. Nickel and lead occurred below their respective analytical detection limits of approximately 0.03 and 0.04 mg/kg wet weight.

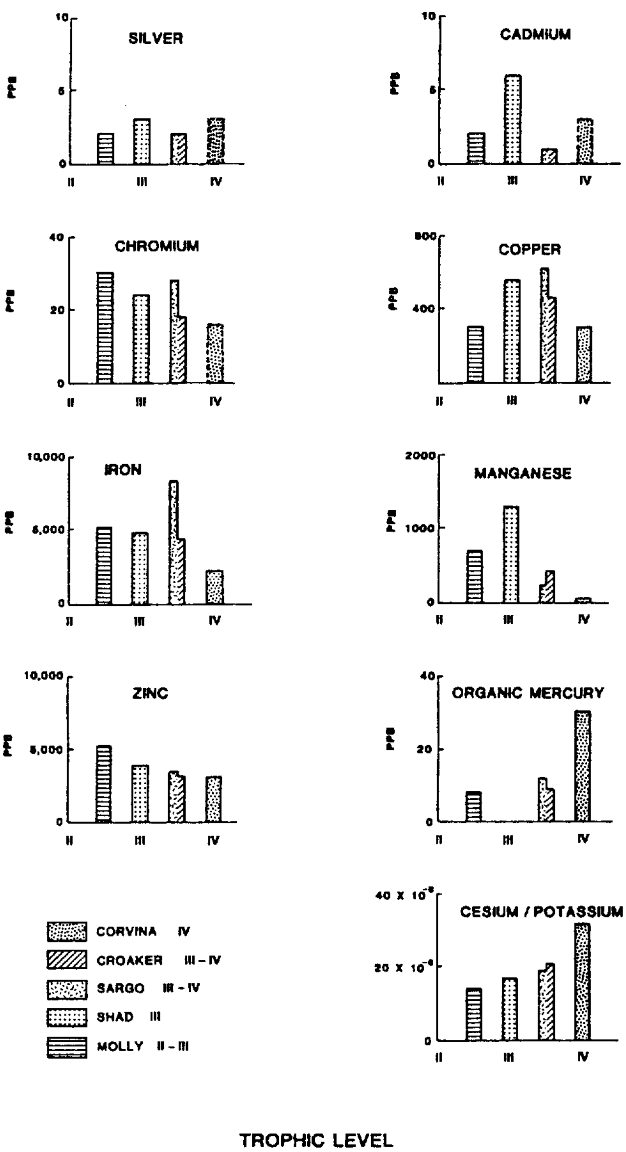

Figure 1. Median values for the Cs/K ratio and eight trace metals (µg/kg wet wt) in muscle tissue vs. estimated trophic level of fishes collected from the Salton Sea in 1978. Silver, cadmium, and chromium values for corvina are upper-limits.

Figure 2 illustrates the sampling area for the benthic seafood organisms collected within the JWPCP outfall monitoring zone. Also shown are isopleths for total chromium in the 1975 surficial sediments (0-5 cm) of this zone. Sediment contamination factors (ratios of median concentrations for the 40-station outfall and the non-discharge baseline zones) obtained from the 1975 survey were: silver-27; cadmium-36; chromium-12; copper-20; mercury-23; nickel-5.4; lead-17; zinc-7.7. Table 1 lists median values for the Cs/K ratios and median concentrations of the five trace metals quantified by AAS in the muscle tissues of the outfall zone seafood samples. Also listed are the trophic level assignments discussed above.

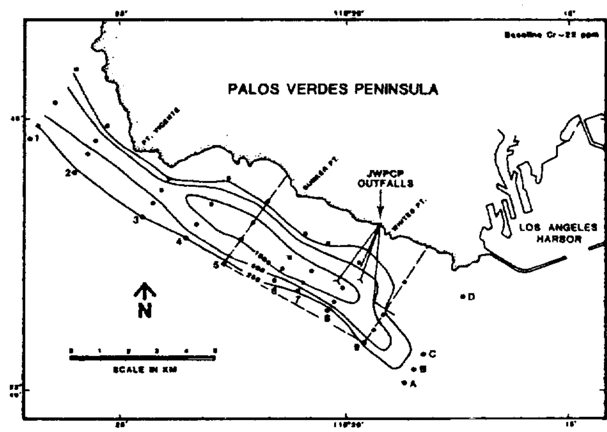

Figure 2. Seafood collection zone (dotted boundary) and sediment chromium isopleths (mg/kg dry wt) within the JWPCP benthic monitoring zone of Los Angeles County Sanitation District. Lines A, B, C, and D are at 1000, 500, 200, and 100 ft water depths, respectively.

Table 1. Estimated trophic level assignments (TLA), and median muscle tissue Cs/K ratios and concentrations (µg/kg wet wt) of trace metals for seafood organisms collected during 1975-77 off the Los Angeles County outfalls.

Organism	TLA	Cs/K x 10^6	Hg	Ag	Cd	Cr	Ni
Abalone	2.00	7.6	11	28	41	950	680
Scallop	2.25	5.4	56	8	800	280	78
Lobster	3.00	—	280	49	19	24	< 50
Crab	3.50	6.5	34	95	4	80	260
Prawn	3.50	11.2	—	—	—	—	—
Sanddab	3.75	12.1	95	5	3	32	56
Croaker	3.75	—	48	19	< 1	59	420
Halibut	4.25	—	250	< 3	< 2	< 14	< 24
Scorpion fish	4.50	13.6	380	22	4	36	150
Bocaccio	4.50	16.6	140	8	< 2	< 10	58

5. DISCUSSION

The data illustrated in Figure 1 suggest that the Cs/K ratio increases exponentially with trophic level. To test this hypothesis, we sought a correlation between the natural logarithm (ln) of the median value for Cs/K x 10^6 for a given organism and its numerical trophic level assignment. The correlation coefficient ($r = 0.93$) was found to be statistically significant, with less than a 5 percent probability of obtaining a value as high as this merely by chance ($p < 0.05$). This indicates that our data are adequately related by the following straight line of best fit:

$$\ln (Cs/K \times 10^6) = m (TLA) + b$$

where $m = 0.49$, $b = 1.36$

It follows directly that the average Cs/K increase factor corresponding to this type of relationship is simply e^m, which in this case has a value of 1.64.

Application of this approach to the Cs/K data from Young's 1967 Salton Sea study (2,3) also yields a statistically significant correlation ($r = 0.98$, $p < 0.01$), with an average Cs/K increase factor of 2.15. We suggest that the lower increase factor for the 1978 study is consistent with the results of biological surveys showing that the food web of the Salton Sea underwent a distinct change between 1967 and 1978; it appears that the introduction of additional intermediate fishes substantially reduced the "structure" of the simple food web found there in 1967. The results for seven of the eight metals illustrated in Figure 1 provide no indication of increasing muscle tissue concentration with estimated trophic level of an organism. In contrast, for at least chromium and zinc there is some suggestion that median concentrations decrease with increasing trophic level assignment. Only in the case of organic mercury do concentrations appear to increase with trophic level. However, no significant correlation ($p > 0.20$) between the logarithm of these (median) concentrations and the TLAs was obtained.

The results for the Palos Verdes outfall study (Table 1) also suggest an increase in the Cs/K ratio with estimated trophic level. Application of the above-described technique again yielded a statistically significant correlation ($r = 0.82$; $p < 0.05$), with an average Cs/K increase factor of 1.41, indicating some degree of structure in this coastal marine food web.

Despite this, the results for Ag, Cd, Cr, and Ni in this highly contaminated ecosystem show no evidence of increased tissue concentration with trophic level assignment. In the case of chromium, there is a very distinct decrease of tissue concentration with TLA in the outfall zone organisms (Figure 3). To see if this also was true for the anthropogenic fraction of the chromium burden, we subtracted the median chromium concentrations measured in muscle tissue of the coastal zone organisms from the corresponding values for the outfall zone specimens. The resultant net median concentrations of "excess" (i.e., anthropogenic) chromium also are plotted against the appropriate TLA values (Figure 3). The logarithmic transformations of both the total and excess chromium concentrations have statistically significant ($p < 0.01$) correlations with the TLA values; resultant average increase factors are 0.15 and 0.21, respectively. These results suggest that, in this discharge zone, chromium builds down, not up, the food web.

Of the five metals investigated, only for mercury did tissue concentrations for the outfall zone specimens appear to increase with trophic level. A statistically significant correlation between ln Hg and ATL was observed ($p < 0.05$), yielding an average increase factor of 2.32. However, when the mercury values were corrected for baseline concentrations measured in the corresponding control zone specimens, no significant relationship was obtained ($p > 0.20$). Thus, this study provided no evidence that concentrations of excess, or anthropogenic, mercury measured in the outfall zone specimens increased with estimated trophic level position.

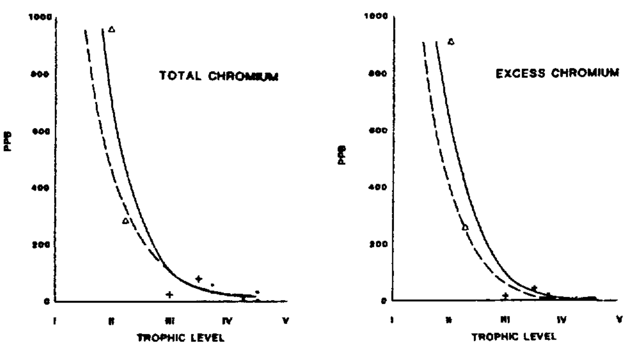

Figure 3. Median muscle tissue concentrations of (total) chromium (μg/kg wet wt) vs. estimated trophic level for seafood organisms collected from the JWPCP benthic monitoring zone during 1975-77. Excess chromium values are measured above baseline values of control zone specimens. Solid and dotted lines are fitted-by-eye, and best-fit exponential curves, respectively.

6. CONCLUSIONS

The Cs/K ratio appears to be a useful indicator of the potential of a given marine ecosystem to biomagnify available constituents with sufficiently long biological half-lives. However in the two metals-rich environments discussed here, with the possible exception of mercury, significant trophic level increases of the target trace metals were not observed.

7. ACKNOWLEDGEMENTS

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