Appendix H

Development of Bioaccumulation Factors for Metals

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H-1 DEVELOPMENT OF BIOACCUMULATION FACTORS FOR METALS

To fully assess the transfer potential of metals in terrestrial ecosystems, it is necessary to monitor various physical, chemical, and biological compartments of the ecosystem. Uptake and accumulation of metals depend not only on the nature and extent of soil contamination and the identity and chemical form of the metals, but also on a number of soil- and organism-related variables. Thus, measurements of bulk metal levels in soil alone are not adequate indicators of metal biotransfer potential. As a result, the degree of applicability of the biotransfer factors to organisms at the Idaho National Environmental and Engineering Laboratory (INEEL) developed from the available literature is uncertain. Table 7-17 summarizes the bioaccumulation factors (BAFs) used.

Biological factors that may influence metal uptake and retention include species, sex, age, diet, tissue examined, and season. Several of these factors are obviously highly interrelated, e.g., diet and season. Diets can vary in metals content and in metals bioavailability to consumers. Even organisms exploiting similar food sources may show considerable differences in metals concentrations from species- and metal-specific differences in the kinetics of assimilation and excretion (e.g., Janssen et al. 1991; Hopkin 1990).

The general pattern of metals accumulation in soil invertebrates is toward higher concentrations in spiders (Arachnida) and detrivores than in herbivorous and carnivorous species (Stafford 1988; Ainsworth 1990a). Because earthworms are an important link in the food chains of insectivorous and carnivorous animals, earthworm uptake of soil-associated chemicals has been more extensively studied than that of other terrestrial soil-dwelling invertebrates. Earthworms at the INEEL occur only on irrigated lawns but may be used as an example of invertebrate bioaccumulation. In general, earthworms provide a good indication of the "worst case" of metal uptake by soil-dwelling invertebrates (Stafford 1988). Thus, BAFs for earthworms may be regarded as a conservative surrogate for other invertebrates. Further, accumulation of certain metals in insectivorous mammals reflect their bioavailability to earthworms (Ma 1987; Scanlon 1987; Hegstrom and West 1989).

The relatively well-studied earthworm system demonstrates some of the complexities of predicting the biotransfer of metals in terrestrial ecosystems. The body concentration of a metal in earthworms is determined by its concentration in soil, the intrinsic rate of bioaccumulation, and the tolerance of the organism to the element. It also depends on the influence of several edaphic factors, notably soil pH, organic matter content, calcium content, and cation exchange capacity (CEC) (Ma 1982; Ma et al. 1983; Corp and Morgan 1991). The bioavailability of several metals to worms appears to be greater in sandy than loamy soils (Ma 1982). CEC, the total amount of cations exchangeably adsorbed by the soil exchange complex, provides an estimate of the capacity of the soil to adsorb heavy metals and gives a measure of the ability of soils to retain these metals against uptake by earthworms (Ma 1982). Significant negative correlations were found between the concentration factor (CF) and the pH of the soil for several metals, including zinc (Ma 1982). For copper, a negative correlation was found with soil organic matter (Ma

1982). Further, the presence and concentration of other metals can have a significant effect on worm uptake of particular metals (Back 1990).

In view of the many gaps in our knowledge of metal biotransfer in the terrestrial environment, the BAFs for the following metals are highly uncertain. An effort has been made to select factors that are protective for use in the assessments at the INEEL. All of these values are in terms of dry weight.

Antimony. The biotransfer of antimony within food chains in a grassland ecosystem in the vicinity of an antimony smelter was studied (Ainsworth 1990 a, 1990b). Several mammalian and macroinvertebrate species at different trophic levels as well as food plants were examined in areas with soil concentrations of antimony ranging from 6.9 to 386 mg/kg near the smelter (Ainsworth 1990b). Tissue concentrations in all species examined were low relative to both soil and dietary concentrations, indicating that the potential for antimony bioaccumulation in terrestrial food chains is low.

For invertebrates, the general trend was toward higher concentrations in the detritivores (e.g., lepidopterans and staphylinids). This trend indicates a pattern of food chain biominification for this metal. As shown in Table H-1, mean BAFs ranged from 0.04 in lepidopterans to 0.9 in Oligochaeta (Ainsworth 1990b), with a geometric mean for all macroinvertebrates of 0.1.

Two herbivorous species, the rabbit (*Oryctolagus cuniculus*) and the short-tailed field vole (*Microtus agrestis*), and one insectivorous specie, the common shrew (*Sorex araneus*) of mammals were examined as available at the study locations. Antimony concentrations were measured for individual organs rather than for the whole body, limiting the usefulness of these data for purposes of estimating food chain exposure. To ensure that bioaccumulation is not underestimated, BAFs were calculated with data from the liver, which contained the highest concentrations of antimony in all species. Results are shown in Table H-2. Although these BAFs are clearly overestimated because antimony concentrations in liver are undoubtedly higher than whole-body concentrations, they are still considerably less than 1.0, indicating no biomagnification of antimony in small mammals. However, the insectivorous shrew appeared to accumulate more antimony than the herbivorous species, perhaps because of greater bioavailability of invertebrate-borne metal (Ainsworth 1990b). The geometric mean BAF for the three species was approximately 0.002. A BAF of 1.0 was used for all functional groups to be protective at the screening level.

Cadmium. Large differences in cadmium concentrations among arthropod and mammalian species collected at the same site have been observed. Laskowski (1991) summarized the available data on cadmium bioaccumulation in terrestrial food chains. The organisms considered included macroinvertebrates as well as the carnivorous shrew (*S. araneus*), and encompassed four trophic levels: herbivores, carnivores, top carnivores, and detritivores. Of 37 reported tissue:dietary concentration ratios identified in the literature for cadmium 26 were greater than 1.0 (Laskowski 1991). Geometric mean values for herbivorous, carnivorous, and detritivorous invertebrates were 1.1, 1.5, and 2.4, respectively. The mean tissue:diet ratio for the shrew was 1.7 (Laskowski 1991). However, the slope of the regression line of dietary to tissue concentrations for all species was only slightly greater than 1.0 (1.3), indicating little potential for biomagnification in the terrestrial food chain. These data, summarized in Table H-3, were used to estimate the following BAFs for terrestrial organisms.

Table H-1. Mean BAFs for antimony in terrestrial macroinvertebrates.[a]

Taxonomic group	Mean BAF (± standard deviation)
Isopoda	0.13 ± 0.13
Diplopoda	0.13 ± 0.12
Lepidoptera	0.04 ± 0.02
Diptera	0.20 ± 0.07
Coleoptera	0.08 ± 0.05
Lycosidae	0.08 ± 0.05
Oligochaeta	0.89 ± 0.21
Overall geometric mean	0.14

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a. Data from Ainsworth (1990a).

Table H-2. BAFs for antimony in small mammals.[a]

Taxonomic group	Mean BAF
Short-tailed field vole	7.8×10^{-4}
Rabbit	3.4×10^{-3}
Common shrew	6.0×10^{-3}
Overall mean	2.5×10^{-3}

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a. Data from Ainsworth (1990a).

Table H-3. Summary of cadmium uptake factors and estimated BAFs in terrestrial ecosystems.

Taxonomic group	Geometric mean ratio of tissue:diet cadmium concentration (dry weight)[a]	BAF
Herbivorous invertebrate	1.1	0.6
Carnivorous invertebrate	1.5	0.9
Detritivorous invertebrate	2.4	7.1[b]
Small mammal (*S. araneus*)	1.7	1.9

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a. Data from Laskowski (1991).b. Derived from a regression equation (Ma 1983) as discussed in text.

b. Derived from a regression equation (Ma et al. 1983) as discussed in text.

Assuming a plant uptake factor (PUF) of 0.55 for cadmium (Baes et al. 1984), a geometric mean tissue-to-soil BAF ratio of 0.6 can be estimated for herbivorous invertebrates by multiplying the two factors:

$$\text{Herbivorous Invertebrate BAF}_{\text{cadmium}} = \text{PUF}_{\text{cadmium}} \times \frac{\text{[Cadmium] in invertebrate}}{\text{[Cadmium] in plants}} \tag{H-1}$$

This value is in good agreement with BAFs for other herbivorous invertebrates reported subsequently (e.g., Lindqvist 1992; Janssen and Hogervorst 1993).

BAFs for cadmium in earthworms and other detritivores are typically higher than those for other soil macroinvertebrates. Uptake by earthworms has been shown to be dependent on many soil parameters, especially pH (Ma 1982), as well as the presence of other metals in the soil (Beyer et al. 1982). Data for earthworms were reviewed by Romijn et al. (1991), who observed that the BAF is not constant but are inversely related to soil concentration. Thus, less cadmium is taken up, relative to soil concentrations, as concentrations increase. Ma (1982) defined the relationship between soil and worm concentrations of cadmium as:

$$\ln \text{[Cadmium] in worm tissue} = 5.538 + 0.664 \ln \text{[Cadmium in soil]} - 0.404\,\text{pH} \tag{H-2}$$

$$\text{Earthworm BAF}_{\text{cadmium}} = \frac{\text{[Cadmium] in worm tissue}}{\text{[Cadmium] in soil}} \tag{H-3}$$

Given the pH ranges identified at the INEEL facility (Martin et al. 1992) and the concentrations of cadmium in the soil (2.2 mg/kg) the earthworm BAFs developed using this equation will range from approximately 4.5 to 7.0.

Assuming that carnivorous invertebrates consume primarily herbivorous species, a BAF of 0.9 can be estimated for carnivorous insects by multiplying the estimated BAF for these prey items (0.6) by the mean ratio of cadmium concentrations in carnivores and herbivores (1.5) (Laskowski 1991):

$$\text{Carnivorous Invertebrate BAF}_{\text{cadmium}} = \text{BAF}_{\text{herbivores}} \times \frac{\text{[Cadmium] in carnivores}}{\text{[Cadmium] in prey}} \tag{H-4}$$

Interspecific variation in cadmium accumulation among mammalian species in the same environment has been observed in several studies (e.g., Anthony and Kozlowski 1982; Scanlon 1987). Data appear to be most abundant for the shrew, which also typically has higher tissue concentrations than herbivorous/omnivorous small mammals (Hunter et al. 1987). Assuming that the BAF of organisms consumed by shrews is approximately 1.1 (the geometric mean of values derived in the equation for carnivorous invertebrates), and the ratio of shrew body burden to prey body burden is 1.7 (Laskowski 1991), a shrew BAF can be calculated by multiplying these two factors:

$$\text{Shrew BAF}_{\text{cadmium}} = \text{BAF}_{\text{prey}} \times \frac{\text{[Cadmium] in shrew}}{\text{[Cadmium] in prey}} \tag{H-5}$$

Thus, the BAF for cadmium in small mammals is conservatively estimated as 1.9.

Chromium. Trivalent chromium is an essential trace element found in all living organisms. Chromium deficiency may result in irreversible metabolic damage. Several researchers have observed that chromium is biominified rather than biomagnified in terrestrial ecosystems. Indeed, in every example reported, chromium concentrations in animals were equal to or lower than those in soils and dietary items (reviewed by Outridge and Scheuhammer 1993). For example, chromium was the least accumulated of eight metals examined by Ma (1982) in earthworms, with a geometric mean of only 0.06 (chromium species not reported) (Ma 1982). In a recent study, BAFs for earthworms were observed to be concentration-dependent (Van Gestel et al. 1993). Further, Beyer et al. (1990) observed no relationship between chromium concentrations in soil and biota at disposal facilities for dredged material. The validity of BAFs derived in the absence of significant correlation is questionable. Such observations indicate that, as expected, chromium uptake is tightly regulated, and is unlikely to be significantly accumulated in the food chain.

In the absence of more definitive data, a BAF of 0.06 for invertebrates shown in Table H-4 is recommended. Because earthworms generally accumulate metals more avidly than other invertebrates, this value is likely to be conservative for soil-dwelling arthropods.

For small mammals, a BAF of 6×10^{-5} has been estimated (VanHorn et al. 1995) as the product of the assimilation efficiency of ingested hexavalent ^{51}Cr in cotton rats, 0.008 (Taylor and Parr 1978) and the PUF for chromium, 0.0075 (Baes et al. 1984). However, because assimilation efficiency refers to dose absorption (i.e., bioavailability) rather than bioaccumulation, this manipulation is inappropriate. The geometric mean BAF for chromium in the house mouse (*Mus musculus*), 0.2, determined by Beyer et al. (1990) is shown in Table H-4.

Copper. Laskowski (1991) summarized available data on copper bioaccumulation in terrestrial food chains. Organisms considered included macroinvertebrates as well as the carnivorous shrew (*S. araneus*) and encompassed four trophic levels: herbivores, carnivores, top carnivores, and detritivores. Of 37 reported tissue:dietary concentration ratios identified in the literature for copper, 22 were greater than 1.0 (Laskowsi 1991). Geometric mean values for herbivorous, carnivorous, and detritivorous invertebrates were 2.5, 1.1, and 0.3, respectively. The mean tissue:diet ratio for the shrew was 0.2 (Laskowski 1991). However, the slope of the regression line of dietary to tissue concentrations for all species was less than 1.0 (0.83), suggesting regulation of copper ion concentrations in terrestrial organisms. These data, summarized in Table H-5, were used to estimate the following BAFs for terrestrial organisms.

Table H-4. Geometric mean BAFs for chromium in terrestrial ecosystems.

Taxonomic group	BAF
Earthworm, arthropod[a]	0.06
Small mammal (*Mus musculus*)[b]	0.20

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[a] Data from Ma (1982).

[b] Data from Beyer et al. (1990).

Table H-5. Summary of copper uptake factors and estimated BAFs in terrestrial ecosystems.

Taxonomic group	Geometric mean ratio of tissue:diet copper concentration (dry weight)[a]	BAF
Herbivorous invertebrate	2.5	1.0
Carnivorous invertebrate	1.1	1.1
Detritivorous invertebrate	0.3	0.34[b]
Small mammal (*S. araneus*)	0.2	0.2

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a. Data from Laskowski (1991).

b. Calculated using regression equation from Ma et al. (1983).

The bioavailability of copper to earthworms appears to be strongly influenced by copper concentration and soil type, but not by soil pH (Ma 1982; Ma et al. 1983; Corp and Morgan 1991). As for cadmium and other metals, less copper is taken up relative to soil concentrations as these concentrations increase. Ma et al. (1983) defined the relationship between tissue and soil concentrations of copper in soil (in mg/kg dry weight) near a zinc smelter as:

$$\text{[Copper] in worm tissue} = 14.88 + 0.344 \times \text{[Copper] in soil} \tag{H-7}$$

$$\text{Earthworm } BAF_{copper} = \frac{\text{[Copper] in worm tissue}}{\text{[Copper] in soil}} \tag{H-6}$$

showing the decreasing BAF with increasing soil concentration. Corp and Morgan (1991) observed a similar relationship in worms exposed to naturally metalliferous soils. In addition, concentration-dependence of the copper BAF for isopods was recently reported (Hopkin et al. 1993). This relationship can be used to calculate site-specific BAFs for copper in earthworms. This formula yields BAFs for earthworms of around 6, 0.9, and 0.4 for soil concentrations of 1 to 10 mg/kg, 0.9 for 10 to 100 mg/kg, and 0.4 for 100 to 1,000 mg/kg.

Assuming a PUF of 0.4 for copper (Baes et al. 1984), a mean tissue:soil BAF of 1.0 can be estimated for herbivorous invertebrates by multiplying this factor by the ratio of copper in animal:plant tissues (2.5):

$$\text{Herbivorous Invertebrate } BAF_{copper} = PUF_{copper} \times \frac{\text{[Copper] in invertebrates}}{\text{[Copper] in plants}} \tag{H-8}$$

This value is in good agreement with subsequently reported BAFs for copper in other herbivorous invertebrates (e.g., Lindqvist 1992; Janssen and Hogervorst 1993). Assuming that carnivorous invertebrates consume primarily herbivorous species, a BAF of 1.1 can be estimated for carnivorous insects by multiplying the estimated BAF for these prey items (1.0) by the geometric mean ratio of copper concentrations in carnivores and herbivores (1.1), reported by Laskowski (1991):

$$\text{Carnivorous Invertebrates } BAF_{copper} = BAF_{herbivores} \times \frac{[\text{Copper}] \text{ in carnivores}}{[\text{Copper}] \text{ in prey}} \tag{H-9}$$

This value is somewhat higher than reported in other studies (e.g., Beyer et al. 1990; Janssen and Hogervorst 1993).

Assuming that the BAF of organisms consumed by shrews is approximately 1.1 (the geometric mean of values derived above for herbivorous and carnivorous macroinvertebrates), and the ratio of shrew body burden to prey body burden is 0.2 (Laskowski 1991), a shrew BAF can be calculated by multiplying these two factors:

$$\text{Shrew } BAF_{copper} = BAF_{prey} \times \frac{[\text{Copper}] \text{ in shrew}}{[\text{Copper}] \text{ in prey}} \tag{H-10}$$

Thus, the BAF for copper in shrews is around 0.2 as listed in Table H-5. This BAF agrees with a BAF value estimated for house mice (Beyer et al. 1990).

Lead. Soil pH and CEC are prime factors in predicting the uptake and accumulation of lead in earthworms (e.g., Ma 1982). Organic matter, calcium, and the presence of other metals are also influential (Terhivuo et al. 1994). In most surveys, the lead BAF for earthworms exceeds unity only when the pH is low (Terhivuo et al. 1994). As for other metals, lead BAFs are typically lower in highly polluted soil. In addition to soil-specific factors, prediction of BAFs for lead in earthworms is complicated by the existence of significant interspecific differences among earthworms exposed to the same soils (Terhivuo et al. 1994).

Ma et al. (1983) and Corp and Morgan (1991) have been developed regression equations for predicting lead BAFs in earthworms. However, the equations supporting their data are dependent on pH, organic matter and calcium concentration. Data on these characteristics are presently lacking for INEEL soils. Until they are available, the following equation Corp and Morgan (1991), which requires pH and concentration of lead in soil and provides a good fit to the data ($r^2 = 93.3$), may be used:

$$\log [\text{Lead}]_{worm} = 2.65 + 0.897 \times \log [\text{Lead}]_{soil} - 3.56 \times \log pH \tag{H-11}$$

$$\text{Earthworm } BAF_{lead} = \frac{[\text{Lead}] \text{ in worm tissue}}{[\text{Lead}] \text{ in soil}} \tag{H-12}$$

As shown in Table H-6, given the pH ranges identified at the INEEL (Martin et al. 1992) and the concentrations of lead in the soil (13 to 72 mg/kg), the earthworm BAFs developed using this equation will range from up to 0.18.

Values derived from this equation agree well with field data reported by Beyer et al. (1990) (0.27 to 0.32) at soil lead concentrations of 21 to 336 mg/kg dry weight).

Hopkin et al. (1993) developed regression equations for lead uptake in the terrestrial woodlice (isopods) *Porcellio scaber* and *Oniscus asellus*. The following equation for *O. asellus* yields slightly higher BAFs, and so is recommended as conservative for use at the INEEL:

$$\log\,[\text{Lead}\,]_{\text{arthropod}} = 0.842 \times \log\,[\text{Lead}\,]_{\text{soil}} - 0.507 \tag{H-14}$$

$$\text{Arthropod BAF}_{\text{lead}} = \frac{[\text{Lead}]\text{ in arthropod}}{[\text{Lead}]\text{ in soil}} \tag{H-13}$$

Given the concentrations of lead in the soil, the arthropod BAFs developed using this equation will range up to 0.290 (in mg/kg dry weight). These BAF values agree with field data reported by Janssen and Hogervorst (1993) (0.01 to 0.43).

Tissue concentrations of lead in insectivorous small mammals generally correlate better with ambient lead concentrations and are higher than those of herbivores (e.g., Beardsley 1978; Ma 1987; Ma et al. 1991). A geometric mean lead BAF of 0.08 for the house mouse (*M. musculus*) can be calculated from the Beyer et al. (1990) data. Whole-body BAFs were not located for insectivorous small mammals, but geometric mean BAFs of 0.6 and 0.2 were calculated for lead in the kidney and liver of the mole (*Talpa europea*) (Ma 1987). Lead concentrations in these tissues were much higher in the shrew (*S. araneus*) than the vole (*M. agrestis*) from the same area (Ma et al. 1991). In the absence of more specifically applicable data, a highly conservative small mammal BAF for lead can be estimated as 0.6 based on the kidney:soil ratio calculated from Ma's (1987) data. A BAF was used for all functional groups to be protective.

Table H-6. BAFs for lead in terrestrial ecosystems.

Taxonomic group	BAF
Earthworm	0.18[a]
Arthropod	0.29[b]
Small mammal (*Talpa europea*)[c]	0.6

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a. Regression equation from Corp and Morgan (1991) as discussed in text.

b. Regression equation from Hopkin et al. (1993) as discussed in text.

c. Based on the geometric mean kidney:soil lead ratio reported by Ma (1987).

Mercury. Large differences in both bioconcentration and toxicity of organic and inorganic mercury have been observed in aquatic ecosystems. While methylation of inorganic mercury by methanogenic bacteria is common in aquatic sediments and greatly facilitates metal uptake, the degree of methylation occurring in terrestrial environments is unclear. The mercury present at the INEEL was conservatively considered to be entirely organic for purposes of TRV development. To avoid overconservatism, mercury in INEEL soils will be considered to be inorganic for BAF development.

Romijn et al. (1991) used available data to calculate a geometric mean BAF of 0.4 for inorganic mercury in earthworms (Romijn et al. 1991). This value also provides a conservative estimate of BAF for other soil-dwelling macroinvertebrates.

Little information regarding bioaccumulation of mercury by other organisms was located. Bull et al. (1977) examined concentrations of mercury in various tissues of woodmice (*Apodemus sylvaticus L.*) and bank voles (*Clethrionomys glareolus Schr.*) collected near a chloralkali plant (mercury contamination ranges from 0.69 to 12.6 mg/kg dry weight) and in an uncontaminated reference area (mercury concentration ranged from 0.04 to 0.19 mg/kg dry weight). As observed with other metals, the BAFs were considerably higher in the control than in the affected area, i.e., uptake decreased with increasing ambient concentration.

Because mercury concentrations in certain areas of the INEEL are greater than background, BAFs from animals collected in the chloralkali plant area are used in this analysis. BAFs for the woodmouse tissues ranged from 0.3 in liver to 1.3 in muscle, while those in bank voles ranged from 0.2 in the brain to 1.2 in hair. Geometric mean BAFs calculated for all tissues examined were 0.7 and 0.4 for woodmice and bank voles, respectively.

The BAF for mercury used in the assessment for appropriate terrestrial functional groups was conservatively based on a study with gray partridges exposed to total mercury for 4 weeks (Eisler 1987), as shown in Table H-7.

Zinc. Like chromium and copper, zinc is an essential trace element for many organisms. As a result, it has received relatively little attention as a potential ecological toxicant in terrestrial ecosystems. Estimated BAFs for zinc in macroinvertebrates and small mammals are presented in Table H-8.

As reported for other metals, zinc BAFs in earthworms appear to be inversely dependent on soil concentration. Van Gestel et al. (1993) reported that the earthworms (*Eisenia andrei*) was able to regulate its body concentration of zinc (around 100 mg zinc/kg tissue) at soil concentrations up to 560 mg/kg. Higher "maintenance" levels in tissues were observed in other species (e.g., Ma et al. 1983; Kruse and Barrett 1985; Beyer et al. 1990). Like cadmium, zinc uptake by earthworms is influenced by soil pH (Ma et al. 1983; Corp and Morgan 1991). However, the available regression equations do not adequately reflect the regulation of zinc concentration evident in field data from several sources. Van Gestel (1993) reported a zinc BAF of 72 at a soil zinc concentration of 1.4 mg/kg. At soil zinc concentrations of approximately 90 to 100, Van Gestel's (1993) and Beyer's groups (1990) reported BAFs of around 1.3. Similarly, BAFs of approximately 0.2 were observed by both groups at soil zinc concentrations of 560 to 570 mg/kg. Zinc BAFs for earthworms should be selected from these ranges on the basis of site-specific soil concentrations (Table H-8).

Table H-7. Mean BAFs for mercury in small mammal tissues[a].

	BAFs	
Tissue	Wood mouse	Bank vole
Brain	0.7	0.2
Hair	1	1.2
Kidney	0.7	0.5
Liver	0.3	0.2
Muscle	1.3	0.4
Geometric mean	0.7	0.4

a. Data from Bull et al. (1977).

Table H-8. BAFs for zinc in terrestrial ecosystems.

Taxonomic group	BAF
Earthworm[a]	
~ 1 mg/kg zinc in soil	72
~100 mg/kg zinc in soil	1.3
~500 mg/kg zinc in soil	0.2
Arthropod	0.83[b]
Small mammal[c]	0.7

a. Data from Beyer et al. (1990) and Van Gestel et al. (1993).

b. Calculated using the regression equation from Hopkin et al. (1993), as discussed in text.

c. Data from Beyer et al. (1990).

Several authors have shown a negative dependence of zinc BAF on soil concentrations in arthropods as well (Lindqvist 1992; Janssen and Hogervorst 1993; Hopkin et al. 1993). The regression equations developed by Hopkin et al. (1993) for the terrestrial woodlice (isopods) (*P. scaber* and *O. asellus*) are representative of these data. The equation for *P. scaber* yields slightly higher BAFs.

$$\log\,[\text{Zinc}\,]_{\text{arthropod}} = 0.274 \times \log\,[\text{Zinc}\,]_{\text{soil}} + 1.890 \qquad \text{(H-15)}$$

$$\text{Arthropod BAF}_{\text{zinc}} = \frac{[\text{Zinc}]\text{ in arthropod}}{[\text{Zinc}]\text{ in soil}} \qquad \text{(H-16)}$$

As shown in Table H-8, given the concentrations of zinc in the soil, the arthropod BAFs developed using this equation range up to 0.83 (in mg/kg dry weight).

A study of zinc accumulation in the organs of granivorous and insectivorous small mammals exposed to sewage sludge containing high concentrations of zinc (and other metals) showed some increase with exposure but no pathological effects (Hegstrom and West 1989). Beyer et al. (1990) reported BAFs for the house mouse (*M. musculus*) of 0.4 to 1.2 exposed to soil concentrations of 74 to 240 mg/kg, with a general trend of inverse relationship to soil concentration. The geometric mean of these data, 0.7, is recommended for use at the INEEL where soil concentrations are compatible (Table H-8). Data are presently lacking to evaluate BAFs at higher soil concentrations. The homeostatic regulation of zinc in most organisms suggests that BAFs will decrease at higher soil concentrations.

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