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Trophic Levels of Small Mammals: Multi-Elemental Composition and Toxic Load

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Abstract—The chemical compositions (25 elements) of the diet and carcass of two sympatric small mammal species (*Clethrionomys glareolus* and *Sorex caecutiens*) inhabiting near a large copper smelter and in unpolluted area (Middle Ural, Russia) have been analyzed and compared. The group of phytophages is shown to play a special role in the translocation of chemical elements over the trophic levels of mammals. Specific features of the diet and a barrier at the gastrointestinal level limit accumulation of chemical elements in the animal body. Under the same conditions, carnivores act in the mammal community as concentrators of several elements (Pb, Cd, Cr, and As), displaying increased their concentrations in the body as compared with the diet. On the other hand, the toxic load on the animal organism is independent of trophic specialization.

Keywords: industrial pollution, chemical elements, small mammals, trophic level, toxic load

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INTRODUCTION

According to the biospheric function of living matter, we should speak about several levels of biogenic cycles of chemical elements formed by living organisms of various trophic specializations. In natural ecosystems, these levels are involved in a sort of "geochemical selection" of microelements (Gol'dshmidt, 1938) determined by differences in their biological accessibility, particular types of chemical compounds in soil, specific types of zonal vegetation, and selective uptake and deposition by animals belonging to different trophic groups (Dobrovol'skii, 1983; Krivolutskii, 1983; Pokarzhevskii, 1985). Actually, there is a complex multilevel geochemical portrait of an integral biogeocenosis and its potential deformation caused by human activities.

So far, a large volume of data has been acquired on accumulation of radionuclides (Pokarzhevskii, 1985; Krivolutskii et al., 1989) and macro- and trace elements including heavy metals (Kabata-Pendias and Pendias, 1986; Sawicka-Kapusta et al., 1986; Lebedeva, 1999) in individual components of natural ecosystems. The papers about of migration of heavy metals in food chains (Bezel et al., 2004; Ma, 1987; Lindquist and Block, 1997; Hamers et al., 2006) including the case of chemical pollution (Bezel, 1987, 2006; Dobrovol'skii, 1988; Mukhacheva and Bezel, 1995; Nyholm, 1995; Medvedev, 1998; Notten et al., 2005; Bezel et al., 2007a, 2007b, 2010) are fewer in number. Research into the trace element composition in populations and communities of various groups constituting biota are important because of the need to clarify the mechanisms underlying establishment of biogenic cycles and the associated methods for control of the anthropogenic impact on the environment.

The aims of this study were to assess the distribution of chemical elements in sympatric populations of small mammals belonging to different taxonomic and trophic groups inhabiting the chemically polluted and background areas.

MATERIALS AND METHODS

The samples obtained while studying populations of wild small mammals (murine rodents and small insectivores) in the vicinity of a large copper smelter and unpolluted areas in the Middle Ural have been analyzed.

The Middle-Ural copper smelter has worked for a long time (since 1940), and the polluted areas around it are distinctly evident. See Vorobeichik et al. (1994) and Mukhacheva (2007) for a detailed description of the test site. Small mammals were trapped in September of 2004 (upon completion of the reproductive season) using baited snap traps and pitfall traps. The animals were simultaneously trapped in two areas: the polluted (impact) site, which was near the source of industrial pollution (1–2 km), and a background site (30 km to the west of the plant) where the contents of

Table 1. Concentrations of the elements in the diets and carcass of bank vole in polluted and background sites (μg/g dry weight)

Element	Site			
	background		polluted	
	diet	carcass	diet	carcass
S	–	18025.9[c] 16545.0–19639.4	–	23419.0[d] 21556.2–25444.7
Cl	–	2693.2 2612.1–2776.9	–	2525.0 2753.2–2898.7
K	24667.0[a] 19253.7–31605.3	9697.6 9367.6–10039.3	16289.4[a] 13377.9–19834.6	9927.9[d] 9744.5–10114.8
Ca	5721.0[a] 4867.7–6723.9	24886.2[c] 23457.5–26402.0	2014.8[a] 1555.5–2609.8	32246.0[d] 29814.4–34876.9
Ti	29.03 25.38–33.20	3.5[c] 3.1–4.0	59.3 34.0–103.5	2.4 2.0–2.9
V	0.4 0.3–0.4	0.09 0.08–0.10	0.35 0.17–0.72	0.08[d] 0.05–0.13
Cr	139.4[a] 96.4–201.7	–	537.4[a] 254.3–1136.0	–
Mn	256.8 226.5–291.1	8.1 7.4–8.8	286.4 212.3–386.5	7.8 6.7–9.1
Fe	460.13 399.73–529.67	361.5[c] 336.1–388.8	1715.6[a] 1215.4–2421.5	298.8[d] 282.8–3156.8
Co	0.16[a] 0.14–0.17	0.09 0.08–0.09	0.57[a] 0.42–0.77	0.08[d] 0.07–0.09
Ni	20.5 18.2–23.1	1.82 1.63–2.03	21.79 15.91–29.84	2.35[d] 1.87–2.95
Cu	19.7[a] 18.7–20.7	5.9 5.7–6.1	105.5[a] 84.4–131.9	7.4 6.9–7.9
Zn	110.2[a] 103.5–117.23	90.3[c] 92.4–96.2	291.4[a] 234.8–361.6	94.8[d] 92.5–97.3
As	0.2 0.1–0.5	1.4 1.1–1.8	–	0.5 0.3–0.7
Br	10.3[a] 9.1–11.7	18.2 16.9–19.6	45.2[a] 27.4–74.6	16.1 14.6–17.7
Rb	33.5[a] 25.3–44.4	17.6[c] 16.5–18.8	14.6[a] 12.5–17.2	21.6[d] 20.4–22.8
Sr	25.8[a] 21.3–31.3	35.2 33.4–37.1	9.4[a] 5.6–15.9	38.7[d] 35.7–41.9
Y	1.9 1.5–2.4	–	2.1 1.8–2.5	–

Table 1. (Contd.)

Element	Site			
	background		polluted	
	diet	carcass	diet	carcass
Zr	–	$\frac{0.6^{c}}{0.4–0.8}$	–	$\frac{1.8^{d}}{1.4–2.3}$
Mo	–	$\frac{0.2}{0.1–0.2}$	–	$\frac{2.3^{d}}{1.7–3.0}$
Cd	–	$\frac{0.5}{0.4–0.5}$	–	$\frac{2.2^{d}}{1.8–2.7}$
Sn	–	$\frac{0.2}{0.2–0.3}$	–	$\frac{0.7}{0.6–1.0}$
I	–	$\frac{0.19}{0.17–0.21}$	–	$\frac{0.85}{0.43–1.70}$
Ba	–	$\frac{28.8}{27.4–30.3}$	–	$\frac{31.5^{d}}{27.6–35.9}$
Pb	$\frac{21.8^{a}}{17.2–27.6}$	$\frac{1.7^{c}}{1.5–1.9}$	$\frac{382.9^{a}}{261.9–560.0}$	$\frac{8.5^{d}}{7.3–9.9}$
n, individuals	5	10	5	5

The numerator is the mean geometric value and the denominator is the minimal and maximal values; a dash denotes the concentration in the sample below the SRXFA detection limit; [a] significant differences between the concentrations of chemical elements in the bank vole diets in background and polluted sites; [b] significance of the differences between the concentrations of chemical elements in the Laxmann shrew diets in background and polluted target sites; [c] significance of the differences between the concentrations of chemical elements in the bank vole carcass in the background and polluted sites; and [d] significance of the differences between the concentrations of chemical elements in Laxmann's shrew carcass bodies in the background and polluted sites; $p = 0.05$.

priority pollutants in the soil did not exceed clark's earth values (Ivanov, 1994).

Two animal species belonging to different taxonomic and trophic groups were selected as model objects, namely, the predominantly herbivorous bank vole (*Clethrionomys glareolus* Shreber, 1780) and the insectivorous Laxmann shrew (*Sorex caecutiens* Laxmann, 1788). These species were selected because they are dominant in the communities of wild small mammals in the examined areas. Separate studies (Mukhacheva, 2005) have shown that the concentration of major pollutants in the animal diet depends by a number of factors: trapping season, age and reproductive status of the animals. Correspondingly, we used the animal samples maximally close in both the trapping period (September 2004) and the reproductuve state (the animals without characteristics of sexual maturity, aged of 3–4 months).

We assume that it is most reasonable when assessing the inflow of various elements into the bodies of small mammals with food to assay the gastrointestinal contents for concentrations of elements, since this provides for taking into account the diet specificity of the studied objects (Mukhacheva and Bezel, 1995). The animal carcass (bodies without internal organs) were prepared for further chemical analysis under cameral conditions. The samples were dried in an oven at 75°C to an air-dry state. Further sample processing and analysis of the chemical composition were performed according to standard protocols (Baryshev et al., 1986; Koutzenogii et al., 2003). The elemental compositions (25 elements) of the diets and carcass of small mammals (15 bank voles and 10 Laxmann shrews) were analyzed by synchrotron radiation X-ray fluorescence analysis (SRXFA) at the Elemental Analysis Station (VEPP-3) with the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences.

The data were processed statistically using log-transformed concentrations of elements. The elements with concentrations in the analyzed sample below the detection limit of the method used were discarded. The quantitative between-group differences in concentrations of elements in the individuals of the compared groups in different sites were estimated using Student's *t*-test ($p < 0.05$).

RESULTS AND DISCUSSION

Diet compositions. The bank vole, being a typical phytophage, feeds on a wide range of forest plants (*Evropeiskaya* ..., 1981; Hansson, 1985). The main diet components of the Laxmann shrew are insects (both larvae and imagoes) and arachnids, while other objects (earthworms, mollusks, plant seeds, amphibi-

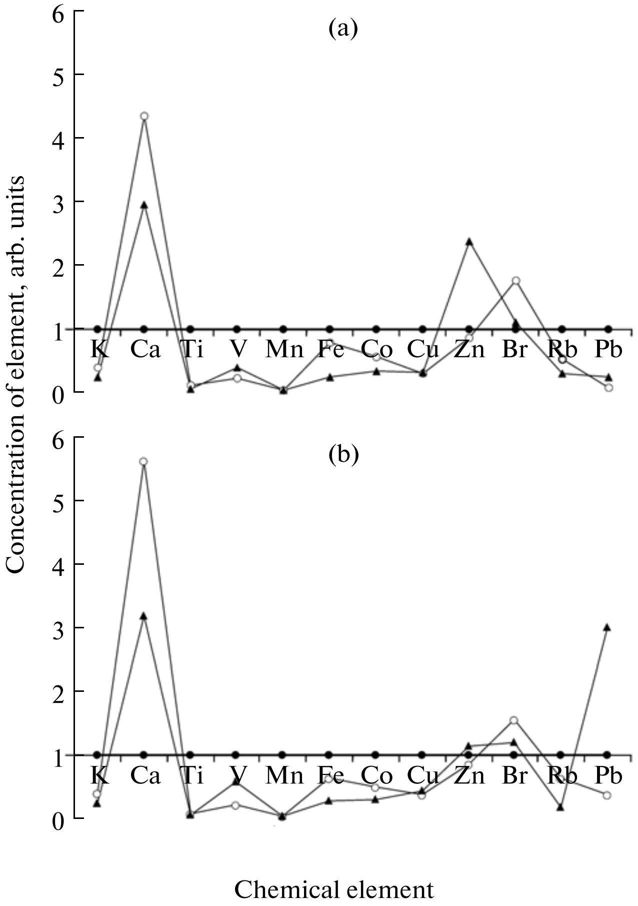

Fig. 1. Concentrations of chemical elements in carcass of animals belonging to different trophic levels relative to the diet of phytophages in (a) background and (b) polluted sites; (○) bank vole; (●) bank vole diet and (▲) Laxmann's shrew.

ans, and mammals) are rarely (Dokuchaev, 1981; Ivanter and Makarov, 2001).

Primary producers form the background of the trophic structure in any system, including the community of small mammals. Under a certain assumption, we may regard the concentrations of chemical elements in the stomach contents of phytophages (bank vole) as reflecting the corresponding concentrations in the biomass of primary producers. Similarly, these concentrations in the stomach contents of the Laxmann shrew are regarded as the chemical composition of the carnivorous diets. Different compositions of the food objects consumed by phytophages and carnivores may also determine the differences in concentrations of trace elements in the bodies of these animals.

Comparison of the background animal diets (within the same trophic group) with the animal diets in impacted areas allows for estimation of the degree of chemical pollution and its qualitative composition. It has been shown that food objects of the bank vole display increased concentrations of Fe and Cr (3.7- to 3.9-fold), Cu (5.5-fold), Zn (2.6-fold), and Pb (17.6-fold). These particular elements should be regarded as the major environmental contaminants. As for Br, its concentration elevated 4.4 (Table 1).

Unlike voles, the diet of Laxmann's shrews in polluted sites is less enriched in Cr (1.8-fold), Cu (3.1-fold), Zn (1.4-fold), and Pb (3.8-fold). The concentrations of the remaining elements in the food objects of Laxmann's shrews inhabiting polluted areas are lower as compared with the background site (Table 2). Thus, most pollutant elements are discriminated as early as the very establishment of carnivorous diets.

Concentrations of elements in carcass of wild small mammals. Having assumed that the concentrations of chemical elements in the diets of phytophages in general reflects their concentrations in the plant objects (primary producers), it is possible to assess accumulation or discrimination of these elements at different trophic levels of mammals in the absence of environmental pollution (Fig. 1a). The concentrations of chemical elements in animal carcasses of both groups almost coincide. Note that the accumulation levels for the majority of assayed elements in the carcasses of both phytophages and carnivores are lower as compared with the diets of phytophages (primary producers). The exceptions are Ca, Zn, and Br, the concentrations of which in the organisms of both bank voles and Laxmann's shrews are higher as compared with the background diets of bank voles.

Comparison of the accumulation levels of chemical elements in animal organisms in the polluted sites with their concentrations in the "polluted" diets of bank voles (primary producers in impacted site) demonstrates a trend similar to that mentioned above (Fig. 1b).

Thus, the majority of chemical elements are evidently discriminated by mammals of different trophic levels at different degrees of environmental pollution. This is most evident for Pb, the minimal concentration of which is recorded in bank vole carcasses. The exception is Ca, since its high concentrations in the organisms of both species are determined by its physiological role.

Interestingly, a 17-fold increase in the Pb concentration in the food objects for bank voles of the impacted site caused only a fivefold increase in its concentration in the carcass (Table 1). As for the carnivores, a 3.8-fold increase in Pb concentration in the "polluted" diets resulted in a 12-fold increase in its concentration in Laxmann's shrew carcass (Table 2). As for the remaining assayed elements, change in their concentration in the diets of insectivorous animals from polluted sites (an increase for Cr, Cu, and Zn and a decrease for Mn, Fe, Co, and Ni) leads to either their insignificant accumulation in the carcass (Cr and Cu) or even a decrease in the concentrations of some elements, namely, Zn, Mn, Fe, Co, and Ni (Table 2).

Consider the general distribution pattern for concentrations of main contaminants in the chain comprising "the diet of phytophages (primary producers)—

Table 2. Concentrations of the assayed elements in the diets and carcass of Laxmann's shrew in polluted and background sites (μg/g dry weight)

Element	Site			
	background		polluted	
	diet	carcass	diet	carcass
S	–	39939.4[c] 32511.2–49064.7	–	33398.6[d] 30649.5–36394.2
Cl	–	3074.2 2718.2–3476.8	–	2624.8 2326.1–2961.9
K	13236.1[b] 4032.5–43445.5	6068.8 5355.5–6877.2	7336.0[b] 6254.0–8605.2	5955.1[d] 5213.4–6802.4
Ca	5276.4 1299.1–21431.1	16957.5[c] 13910.4–20671.9	2451.6 1816.8–3308.2	18236.5[d] 14456.0–23005.6
Ti	204.1[b] 37.9–1100.7	1.5[c] 0.9–2.6	41.9[b] 32.0–54.8	1.9 1.2–3.0
V	1.2[b] 0.2–6.3	0.2 0.1–0.3	0.3[b] 0.2–0.3	0.2[d] 0.1–0.3
Cr	185.2 30.3–1132.2	0.6[c] 0.5–0.8	340.8 207.5–559.8	1.4 1.0–2.0
Mn	244.8[b] 62.2–963.1	8.4 6.1–11.3	129.3[b] 119.4–140.1	9.7 7.3–12.9
Fe	2188.8 526.8–9093.3	115.3[c] 91.2–145.6	1200.2 1068.9–1347.6	127.6[d] 114.7–142.0
Co	0.60 0.16–2.24	0.05 0.05–0.06	0.37 0.34–0.40	0.05[d] 0.04–0.05
Ni	10.3[b] 2.9–37.1	0.9 0.7–1.1	6.0[b] 5.5–6.6	0.7[d] 0.6–0.9
Cu	26.4[b] 7.8–89.2	6.2[c] 5.6–6.8	82.6[b] 76.1–89.6	8.6 8.2–9.0
Zn	252.0 78.4–810.6	262.4[c] 206.9–332.8	341.3 310.4–375.2	126.3[d] 111.0–143.8
As	1.0 0.2–3.9	–	1.0 1.0	–
Br	16.5 5.4–50.9	11.4 10.0–12.9	15.0 13.1–17.1	12.4 10.5–14.7
Rb	15.0[b] 4.5–50.1	9.8[c] 7.8–12.2	4.0[b] 3.4–4.7	5.7[d] 5.1–6.5
Sr	17.9 4.4–72.5	28.9 24.5–34.3	1.0 1.0	25.1[d] 19.3–32.7
Y	1.56 0.4–5.7	0.5 0.4–0.5	1.1 0.8–1.4	0.3 0.1–0.6

Table 2. (Contd.)

Element	Site			
	background		polluted	
	diet	carcass	diet	carcass
Zr	–	0.10^{c} 0.06–0.15	–	0.07^{d} 0.04–0.14
Mo	–	0.2 0.2–0.3	–	0.3^{d} 0.3–0.4
Cd	–	0.3 0.2–0.4	–	0.6^{d} 0.5–0.8
Sn	–	0.7 0.3–1.4	–	1.2 0.9–1.4
I	–	0.3 0.2–0.5	–	0.5 0.4–0.6
Ba	–	3.9^{c} 1.9–8.2	–	7.6^{d} 5.8–10.0
Pb	72.9^{b} 16.6–319.9	5.4^{c} 4.6–6.4	277.6^{b} 173.3–444.6	65.5^{d} 5.8–115.6
n, individuals	5	6	4	4

See Table 1 for designations.

body of phytophages—diet of carnivores—body of carnivores (consumers)" for the polluted area (Fig. 2). A certain periodicity of the change in concentrations of priority pollutants (Cu, Zn, and Pb) is evident: the contents of elements in the bank vole and Laxmann's shrew diets somewhat exceed the corresponding concentrations in their organisms. Other elements (for example, Ti and Co) display a similar pattern. It is necessary to emphasize that here we speak about trophic levels in general, since phytophagous animals in our case should not be regarded as a component of the food chain, that is, the food objects of Laxmann's shrews.

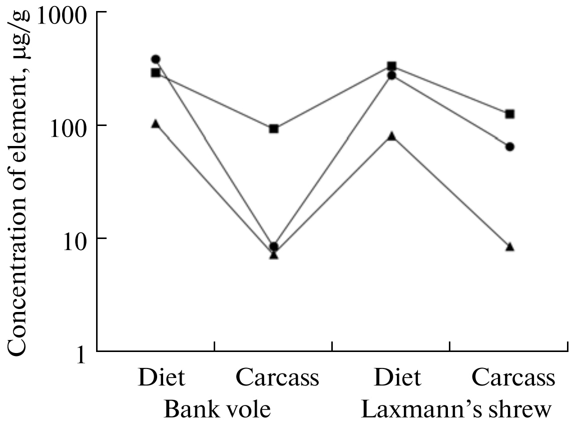

Fig. 2. Changes in concentrations of priority pollutants (µg/g dry weight) according to trophic levels of mammals: (▲) Cu; (■) Zn, and (●) Pb.

It is known that Laxmann's shrew mostly forages in the ground–litter layer (Ivanter and Makarov, 2001) and its diet mainly consists of arachnids, ground beetles (Carabidae, Elateridae, and Staphylinidae), dipteran larvae, hemipterans, and earthworms. According to Vorobeichik et al. (1994, 2007), the soil mesofauna of impacted area undergoes cardinal changes as compared with background areas. Some groups in the impacted site disappear completely (Lumbricidae, Enchytraeidae, Diplopoda, and Mollusca), while other groups (Carabidae, Staphylinidae, Arachnidae, and Diptera) drastically decrease their abundance. A characteristic feature of the populations in polluted areas is an increase in the proportion of elaterid larvae from 0.7–4.0% (background site) to 35–50%, accompanied by an increase in the abundance parameters. For example, 10–30% of the total population are confined to the litter in background site versus up to 50–80% in the site at a distance of 1–2.5 km from the pollution plume.

Our earlier analysis of the major pollutants in representatives of various invertebrate groups (Bezel et al., 2004, 2010) suggests that their accumulation is species-specific. An intricate process of carnivorous diet formation is the particular factor that determines the concentrations of elements in the stomach contents of Laxmann's shrew, including an elevated content of certain elements, such as Pb, Rb, Fe, and Co, in their food objects (Table 2).

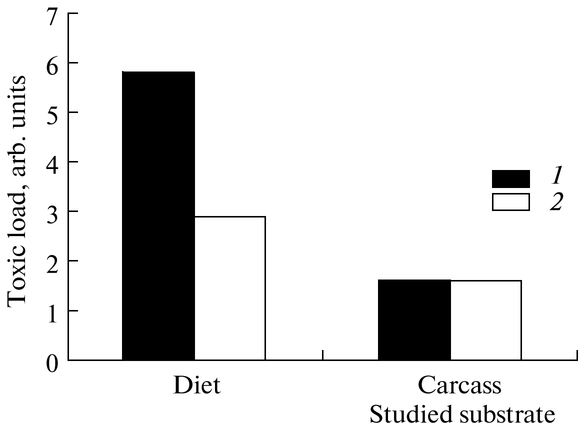

Fig. 3. Toxicity of the diets and toxic load on the organisms of animals belonging to different trophic groups in the polluted site: (*1*) bank vole and (*2*) Laxmann's shrew.

Thus, the trophic levels of mammals in the case of chemical pollution act as certain "geochemical barriers" by interfering with active transmission of the pollutant elements to higher trophic levels in ecosystems.

An integral characteristic, the total toxic load, is convenient to estimate the degree of impact of chemical pollution on an animal organism:

$$S_n = (l/n)\Sigma c_i/c_f,$$

where n is the number of considered elements; c_i and c_f are the concentrations of the elements that may be regarded as toxic in the polluted and background sites, respectively. This characteristic can be calculated for both situations—for the toxicants entering the body with feed (food toxic load) and for accumulation of elements in animal tissues as a toxic load on the organism (Mukhacheva and Bezel, 1995; Bezel et al., 2007b).

Our estimates demonstrate that the toxic load formed by chemical elements in the diet of phytophages is maximal. It is noteworthy that this high toxicity of the bank vole's diet involves a wide range of elements—Ti, V, Cr, Co, Cu, Zn, As, Cd, and Pb (Bezel et al., 2007a). Such a "feed load" is twofold lower for Laxmann's shrew and is mainly formed by Cu, Cd, and Pb. On the other hand, the toxic load on small mammal's organism (calculated forcarcass) is independent of their trophic specialization (Fig. 3).

CONCLUSIONS

Thus, phytophages play a special role in the distribution of chemical elements over trophic levels. Specific features of the diet and the barrier at the gastrointestinal level limit the input of chemical elements into the animal body from the primary producers to organisms of higher trophic levels. Under the same conditions, carnivores in the mammal community act as concentrators of several elements (first and foremost, lead), displaying increased concentration in their organisms as compared with the corresponding concentrations in the food objects.

Under conditions of chemical pollution, the total toxic load on consumers is independent of the trophic specificity of the studied animals but is rather primarily determined by the fact that both species belong to mammals and have similar physiological mechanisms for the uptake and deposition of the assayed elements.

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