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Long-term Dynamics of Heavy Metal Concentrations in the Food and Liver of Bank Voles (*Myodes glareolus*) in the Period of Reduction of Emissions from a Copper Smelter

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Abstract—Long-term changes in the contents of heavy metals (Cu, Zn, Cd, Pb) in the food and liver of bank voles (*Myodes glareolus*) inhabiting areas exposed to pollution from the Middle Ural Copper Smelter (MUCS) in the period of reduction of its emissions (1990–2015). The results show that 50-fold reduction of emissions has not resulted in an equivalent decrease in the dietary and body concentrations of metals: in the impact zone (1–2 km from the MUCS), Cu, Zn, and Pb concentrations remain unchanged, while Cd concentrations have increased twofold by the end of the observation period; in the background zone (20 km), Cu, Zn, and Cd concentrations remain unchanged, while Pb concentrations have decreased by a factor of 1.7–2.5; and no directed changes have been revealed in moderately polluted plots (4–6 km). The accumulation of heavy metals in the animal body depends primarily on the contents of these elements in food and on the system of element-specific homeostatic barriers providing effective protection from the toxic effect of heavy metals.

Keywords: industrial pollution, copper, zinc, cadmium, lead, small mammals, liver, vegetation

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Industrial emissions have been reduced worldwide during the past few decades as a result of closing outdated plants and improving production technologies. However, unless remediation measures are taken, many pollutants, including heavy metals (HMs), can long persist in ecosystems around point polluters [1–3], circulate in food chains [4], and exert adverse effect on the biota [5–8]. Therefore, information on not only the dynamics of input but also on the contents of pollutants in different components of the biota is necessary for understanding the patterns of ecosystem recovery after reduction of emissions.

Small mammals are widely used in ecotoxicological research due to their widespread occurrence, high abundance, resident mode of life, eurybiontic properties of many species, and important role in terrestrial ecosystems [9, 10]. Studies on the response of these animals to pollution are usually limited to analysis of changes in their species diversity and abundance [11–13] or of HM contents in depot organs [14, 15], sometimes with reference to morphological, biochemical, and genetic data [8, 16–18].

In most cases, the results of studies on small mammal communities represent a "short time section," since the period of observations is only 1–3 years. Long-term regular observations (for more than 10–15 years) under conditions of industrial pollution are few [19–22]. Data on the long-term dynamics of elemental composition of the body and food objects in small mammals are fragmentary [8, 23], although relevant studies have been performed on other groups of vertebrates, particularly birds [5–7, 24].

Such studies on small mammals make it possible to estimate the dynamics of toxic load at two levels simultaneously: the concentrations of elements in stomach contents characterize the intake of pollutants with food, and data on their accumulation in depot organs are indicative of their possible toxic impact on animal organism.

During the past 25 years, we have performed annual surveys of small mammal communities in areas exposed to emissions from the Middle Ural Copper Smelter (MUCS), which has been in continuous operation for 75 years. As a result, a high-contrast geochemical anomaly has developed in its vicinities, with the contents of HMs and other elements in the soil exceeding the background level by one to two orders of magnitude [1]. Emissions from the MUCS have been gradually reduced since 1998, which allowed us to compare the status of small mammal communities in the periods of heavy emissions, their significant reduction, and almost complete cessation. Throughout the observation period, animals have been trapped using stationary trap lines, which made it possible to minimize spatial variation in the test parameters. The results of our previous research provide evidence for distinct seasonal specificity in the accumulation of HMs in the food of voles [25] and for the effect of age on their accumulation in the body [26]. Therefore, the scope of this study is limited to animals of only one species and of similar age (young of the year) trapped during the same period (June to September).

The purpose of this study was to analyze the dynamics of HMs (Cu, Zn, Cd, Pb) in the food and liver of bank voles (*Myodes glareolus* Schreber 1780) during the period of reduction of emissions from the MUCS. The hypothesis to be tested was that reduction of emissions leads to decrease in HM concentrations, with this decrease being manifested more strongly in the immediate vicinity of the emission source than in more distant areas.

MATERIAL AND METHODS

Emission source. The MUCS, located 50 km west of Yekaterinburg (56°51′ N, 59°53′ E), is Russia's largest works producing crude copper and sulfuric acid, which has been in operation since 1940. The main toxic components of its emissions are SO_2 and dust containing HMs and metalloids. Total annual emissions reached $150–225 \times 10^3$ t in the 1980s, $95–100 \times 10^3$ t in the 1990s, decreased to 30×10^3 t in the mid-2000, and have not exceeded $2.5–5 \times 10^3$ t since 2010, after refurbishment was completed [27]. Thus, gross emissions have been reduced almost 50-fold during the past 25 years, with the concentration of SO_2 decreasing by a factor of 80 and those of Cu, Zn, and Pb by factors of 3000, 15, and 8.5, respectively [1]. We arbitrarily divided the past 25 years into three periods: (I) 1990–1997, consistently high emissions; (II) 1998–2009, markedly reduced emissions; and (III) 2010–2015, minimal emissions.

Animal trapping. Small mammals were trapped every year, from May to September 1990–2015, in spruce–fir forests growing west of the MUCS (against the prevailing wind direction) at different distances from it: 1–2 km (impact zone), 4–6 km (buffer zone) and 20 km (background zone). Three to nine stationary trap lines were established in each zone at a distance of 100 to 1000 m from each other. A line consisted of 25 snap traps placed at intervals of 5–7 m, which were exposed for 4 days and checked once daily. Trapping was carried out in all test plots simultaneously. On the whole, more than 6500 small mammals were trapped over about 85000 trap–days.

Bank voles dominated in small mammal communities of all zones, with their proportion averaging from about 50% in polluted plots to 75% in background plots. Trapped animals were examined to determine their age, sex, and reproductive status. To avoid bias resulting from seasonal and age-dependent differences in HM accumulation, only young of the year trapped in July to September were included in analysis.

Chemical analysis of samples. A fragment of the liver and stomach contents from each animal were dried at 75°C to air-dry weight and sealed in plastic bags. Samples delivered to the laboratory were minced and weighed on a KERN-770 analytical balance to an accuracy of 0.01 mg. Aliquots of about 100 mg were placed in Teflon bombs with a mixture of 7 mL 65% HNO_3 (ultra high purity) and 1 mL deionized H_2O, incubated for 30 min, and incinerated in an MWS-2 microwave oven (Berghof, Germany). Sample volume was then adjusted to 10 mL with deionized H_2O.

The concentrations of HMs (μg/g dry weight) were measured in AAS 3 and AAS vario 6 atomic absorption spectrometers with flame (for Cu and Zn) or electrothermal (for Cd and Pb) atomization. Analysis was performed at the Laboratory of Ecotoxicology of Populations and Communities (Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences) certified for technical competence (certificate no. ROSS RU.0001.515630). The quality of measurements was estimated with reference to the CRM 185R (Bovine Liver) standard. Extraction percentages were 93.2% for Cu, 99.8% for Zn, 114.2% for Cd, and 94.4% for Pb; the respective detection-limit concentrations were 0.013, 0.005, 0.001, and 0.013 μg/mL. If the element concentration was below the detection limit, a value equal to half of the detection limit was used for statistical calculations. A total of 1109 liver samples and 487 samples of stomach contents were analyzed.

Statistical analysis. In most cases, the distribution of HM concentrations was close to lognormal. Descriptive statistics such as the geometric mean, range, and variation coefficient (*CV*) were calculated for these concentrations, with Finney's method for lognormal variables [28] being used to obtain unbiased *CV* estimates. Calculations were made with EnvStat v. 2.1.1 [29]. Two-way ANOVA was used to reveal differences in HM accumulation between test plots and periods (the data were converted into logarithmic form). Multiple comparisons were made using Tukey's test. The relationship between HM concentrations in the food and liver was analyzed by calculating the linear correlation coefficient. Regression analysis was used to evaluate long-term changes in HM concentrations. Differences were considered statistically significant at $p < 0.05$. Calculations were made using JMP v.11.

RESULTS

Metal concentrations in food. The accumulation of each HM in food (Table 1) was dependent on the level of pollution and the period of observation (Table 2). During period I, HM concentrations in the food of voles from the buffer and impact zones significantly exceeded the background level: by factors of 4.0–7.8 for Cd, 3.6–6.9 for Cu, 1.8–4.1 for Pb, and 1.2–2.3 for Zn. By period III, differences in Cu and Zn between

Table 1. Heavy metal concentrations in the food of bank voles from the study region in different periods, μg/g dry weight

Zone	Period	*N*	Cu		Zn		Cd		Pb	
Background	I	49	13.55 [58.9] (3.85–53.21)	a	76.98 [63.1] (18.26–416.01)	a	0.38 [95.6] (BDL–3.09)	a	6.01 [179.0] (0.50–45.12)	a
	II	174	20.92 [60.6] (3.27–100.67)	b	97.03 [49.6] (19.06–97.03)	b	0.99 [109.9] (BDL–14.43)	b	4.78 [163.2] (BDL–60.75)	a
	III	48	15.31 [56.9] (4.45–42.87)	a	82.21 [147.7] (37.05–194.69)	ab	0.64 [105.6] (BDL–6.48)	ab	2.18 [96.5] (BDL–11.46)	b
Buffer	I	54	48.39 [89.0] (6.52–270.31)	a	90.23 [102.5] (22.98–714.78)	a	1.52 [154.7] (0.05–18.34)	a	10.75 [177.3] (0.13–88.17)	a
	II	55	82.62 [65.9] (17.23–330.04)	b	143.55 [56.6] (29.04–409.83)	b	3.94 [114.9] (0.05–36.07)	b	17.22 [252.1] (0.16–127.24)	a
	III	25	50.38 [97.7] (9.83–160.98)	a	117.76 [75.2] (20.63–280.83)	ab	2.02 [102.1] (0.25–12.23)	a	13.77 [106.1] (1.97–53.58)	a
Impact	I	43	93.73 [88.9] (8.14–542.52)	a	176.01 [78.5] (19.17–474.43)	a	2.97 [97.8] (0.37–13.44)	a	24.44 [176.7] (1.41–198.01)	a
	II	27	131.64 [54.1] (41.31–436.50)	a	175.00 [39.5] (92.92–402.01)	a	5.97 [91.0] (1.51–13.78)	b	44.26 [130.9] (1.86–346.39)	b
	III	11	83.28 [76.7] (34.17–441.95)	a	151.92 [45.0] (81.63–306.77)	a	6.07 [61.6] (3.09–25.26)	b	21.36 [96.1] (4.64–83.01)	a

The values shown here and in Table 3 are geometric means with variation coefficients (%, in square brackets) and extremes (in parentheses); BDL, values below detection limit. Similar letters indicate the absence of significant differences in element concentration within the zone (Tukey's test).

Table 2. Results of ANOVA for differences in heavy metal concentrations in the food and liver of bank voles between pollution zones and periods (*F* test, values in parentheses show significance level; *N,* number of samples)

Source of variation	df	Cu	Zn	Cd	Pb
			Food		
Zone	2	259.6 (<0.0001)	33.6 (<0.0001)	66.6 (<0.0001)	69.2 (<0.0001)
Period	2	20.3 (<0.0001)	5.9 (0.003)	15.9 (<0.0001)	4.9 (0.008)
Zone × period	4	0.6 (0.698)	1.9 (0.102)	0.4 (0.822)	3.2 (0.013)
N		487	475	485	471
			Liver		
Zone	2	69.5(<0.0001)	13.4 (<0.0001)	745.9(<0.0001)	65.7(< 0.0001)
Period	2	25.8 (<0.0001)	19.3 (<0.0001)	56.8 (<0.0001)	6.6 (0.002)
Zone × period	4	1.3 (0.287)	1.7 (0.138)	2.1 (0.081)	5.7 (< 0.0001)
N		1109	1104	1099	1074

polluted and background plots either remained unchanged or decreased slightly (primarily on account of impact values). Conversely, the differences in Cd and Pb concentrations increased and became almost 10-fold in the impact zone. This was explained by distinct trends in the concentrations of these metals in the polluted and background areas (Fig. 1): dietary Cd concentrations in the impact zone were increasing at a rate of 2.1% per year, which resulted in a twofold increase over 25 years (compared to period I); on the other hand, Pb concentrations in the background zone were decreasing at an annual rate of 2.1% and eventually decreased 2.8-fold over the same period. No distinct trends were revealed in the buffer zone. Strong variation in HM concentrations was observed in all plots throughout the study period, with its range being relatively narrow for essential Zn and Cu and two to four times wider for toxic Pb and Cd.

Metal concentrations in the liver. The accumulation of HMs in the liver was also dependent on the level of pollution and the period of observation, with the interaction of these factors also having a significant effect (Table 2). During period I, the concentrations of Cu and Zn in polluted plots exceeded the background

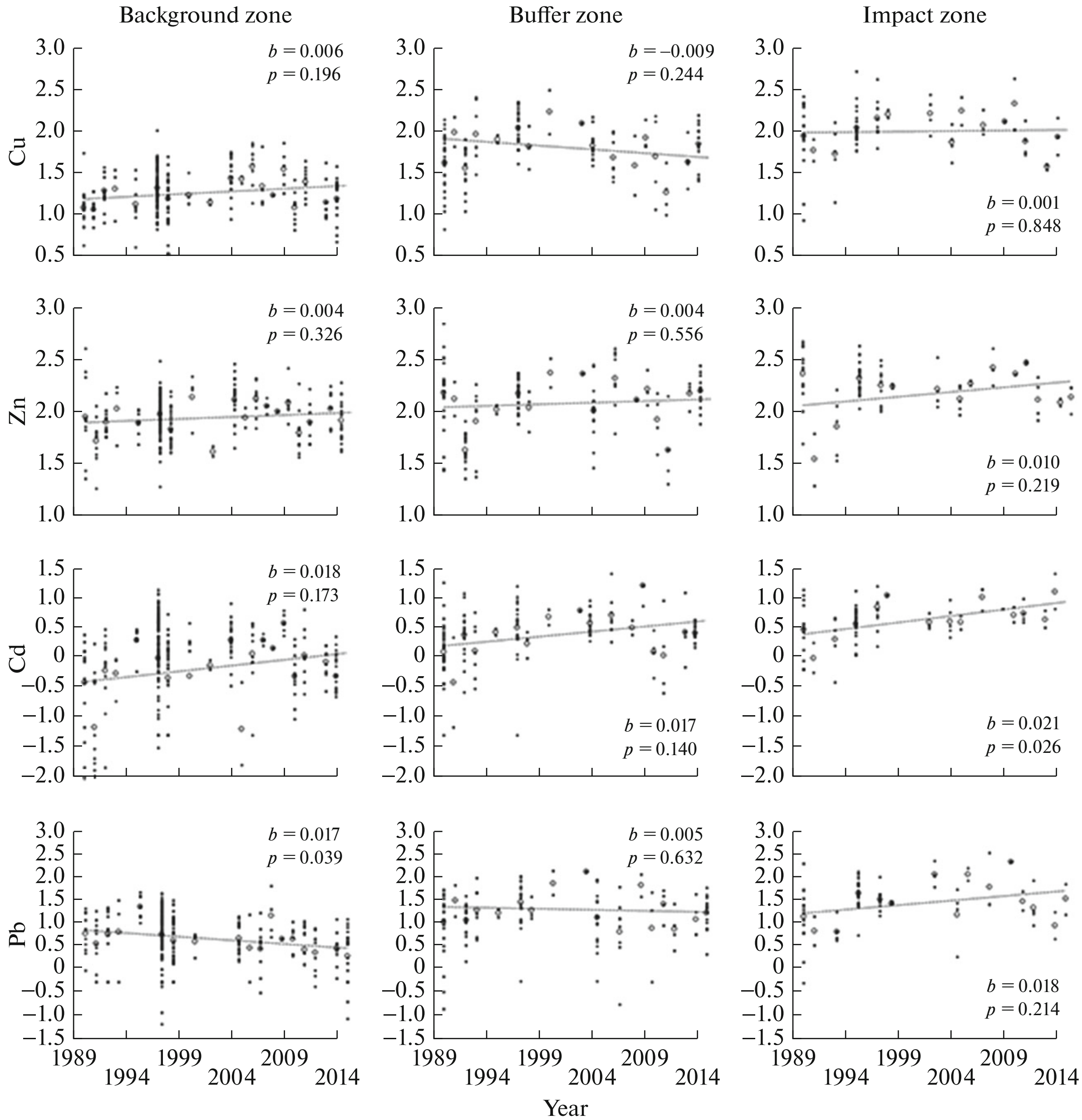

Fig. 1. Long-term dynamics of heavy metal concentrations (μg/g dry weight, logarithmic values) in the food of bank voles from zones with different pollution levels. Here and in Fig. 2: (●) individual values, (○) annual average values; *b,* regression coefficient; *p,* significance level.

levels by a factor of 1.1–1.3; of Pb, by a factor of 1.6–1.9; and of Cd, by a factor of 7.0–8.1 (Table 3). As in the case of vole food, differences in Cu and Zn concentrations between the background and polluted plots remained at the same level by period III, whereas those in Pb and Cd concentrations increased to 3- and 12-fold, respectively. This was due to trends in metal concentrations (Fig. 2): liver Cd concentrations in the impact zone increased at an annual rate of 2.4%, which resulted in a twofold increase over 25 years, while Pb concentrations in the background zone decreased at an annual rate of 2.6% and eventually became 1.7 times lower, compared to the initial values. No distinct trends were revealed in the buffer zone. The concentrations of HMs in the liver of animals from all zones strongly varied throughout the study period. The narrowest variation range was observed for essential Zn and Cu, with *CV* values being two to seven times lower than those for dietary elements; the *CV* values for toxic Cd and Pb in the food and liver were comparable (Tables 1, 3).

Relationship between metal concentrations in food and liver. The concentrations of HMs in the food and liver of voles were correlated with each other (Fig. 3).

Table 3. Heavy metal concentrations in the liver of bank voles from the study region in different periods, μg/g dry weight

Zone	Period	*N*	Cu		Zn		Cd		Pb	
Background	I	260	11.37 [35.2] (4.26–45.50)	a	82.95 [38.3] (20.47–187.45)	a	0.76 [95.0] (0.02–11.64)	a	1.51 [93.1] (BDL–12.54)	a
	II	120	14.12 [21.9] (8.37–23.26)	b	95.29 [17.6] (57.28–235.42)	b	1.27 [74.0] (0.03–5.45)	c	1.14 [76.9] (BDL–7.07)	b
	III	123	11.99 [26.4] (5.45–21.41)	a	98.88 [10.4] (72.55–137.10)	b	0.99 [72.5] (0.16–7.38)	b	0.87 [125.5] (BDL–8.85)	c
Buffer	I	205	14.72 [45.7] (5.68–46.85)	a	90.70 [43.8] (27.55–247.03)	a	6.12 [132.9] (0.05–54.82)	a	2.38 [132.9] (BDL–17.15)	a
	II	83	18.12 [44.4] (7.83–81.36)	b	105.62 [14.4] (73.76–136.56)	b	10.59 [104.3] (1.43–58.39)	b	2.01 [120.7] (0.19–14.04)	a
	III	67	16.50 [32.7] (8.88–32.7)	ab	105.43 [11.4] (75.41–138.43)	b	8.36 [81.0] (0.73–26.10)	b	1.70 [83.9] (BDL–13.61)	a
Impact	I	159	15.07 [31.1] (6.81–47.92)	a	101.12 [26.8] (33.49–163.47)	a	5.28 [92.7] (0.56–33.10)	a	2.90 [135.8] (0.04–14.16)	a
	II	69	16.82 [25.6] (8.99–28.12)	a	105.54 [13.9] (72.19–133.82)	a	11.43 [88.4] (1.58–62.76)	b	4.73 [77.2] (0.79–16.21)	a
	III	23	16.55 [23.2] (9.13–24.31)	a	106.32 [15.0] (86.77–180.39)	a	11.51 [67.1] (4.97–61.31)	b	2.76 [151.9] (0.05–12.20)	a

In the pooled sample from all the plots ($n = 274$–286), pairwise correlation coefficients between these concentrations proved to be statistically significant for all elements ($r = 0.24$–0.46, $p < 0.0001$). Differential analysis of samples from individual zones showed that this correlation in the background plot was significant only for Cd ($r_{Cd} = 0.22$, $n = 126$, $p = 0.012$); in the buffer zone, only for Cu ($r_{Cu} = 0.25$, $n = 99$, $p = 0.014$); and in the impact zone, for all HMs except Pb ($r_{Cu} = 0.36$, $n = 62$, $p = 0.004$; $r_{Zn} = 0.36$, $n = 62$, $p = 0.004$; $r_{Cd} = 0.29$, $n = 62$, $p = 0.022$).

DISCUSSION

Long-term dynamics of HM concentrations in food. The food spectrum of the bank vole is fairly wide [30], with green plant parts, seeds, berries, and fungi prevailing in the diet during the summer–autumn period. Therefore, HM concentrations in the stomach contents of these animals may be regarded as an integrated indicator of the pollution of vegetation (primarily herbaceous) in a given area in a given moment of time [25].

It could be expected that 50-fold reduction of emissions would result in a decrease in pollutant concentrations in plants. However, no equivalent change in the level of TM accumulation was revealed in the food of bank voles. During the 25-year observation period, changes in the concentrations of essential elements (Cu and Zn) in the food of voles from a given zone varied within a given zone were nondirectional and minor (by no more than 20%), whereas the concentrations of toxic Cd and Pb changed significantly and in different directions. By the end of the study (period III), Pb concentrations in the food decreased in all zones, whereas Cd accumulated at a high rate in the food of voles from polluted areas during periods I and II. Moreover, when emissions were abruptly reduced (period II), Pb and Cd concentrations in food were even found to increase in polluted areas. Thus, Pb concentration in the food of voles from the impact zone during this period was approximately twice higher than during periods I and III: 44.26 vs. 24.4 and 21.3 μg/g, respectively (Table 1).

The significant increase in the concentration of Cd in the food of voles from polluted areas may be due to its accumulation in the humus horizon and forest litter, where the contents of this element were shown to increase 1.5- to 2-fold and, in places, even 4-fold between 1989 and 2012 [1]. According to the authors [1], changes in soil acidity were the main factor responsible for Cd accumulation in these horizons. In the period of high emissions (I), the pH of the litter and humus horizons was low (3.5–4.2), providing for active Cd leaching to the underlying layers. When emissions almost ceased, the pH of both horizons increased to 4.6–5.0, with consequent decrease in Cd mobility and its accumulation in the root soil layer, which probably accounted for more active Cd uptake by plants.

It was interesting to compare pong-term changes in the contents of HMs in the stomach contents of voles and in their potential food plants. Unfortunately, there is no information on the long-term dynamics of HM concentrations in plants growing in the vicinity of MUCS. Available data concern the concentrations of Cd, Pb, Cu, and Zn in some herbaceous plants [30,

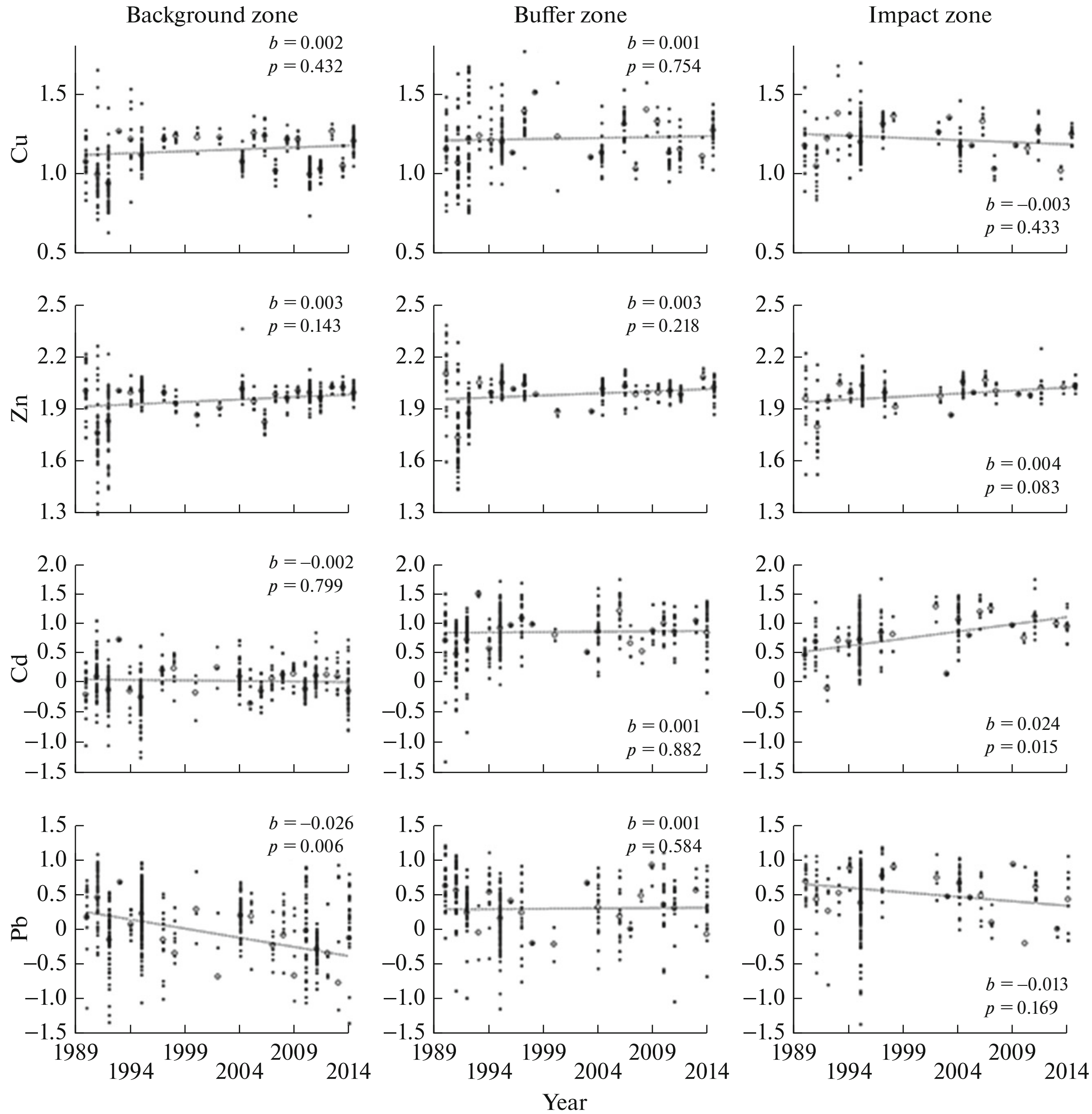

Fig. 2. Long-term dynamics of heavy metal concentrations (μg/g dry weight, logarithmic values) in the liver of bank voles from zones with different pollution levels.

32], wild berries [31, 33], and pileate fungi [31] in the period of reduced emissions (2006–2009). Their concentrations on the impact zone markedly exceeded the background values: in vegetative plant parts, the maximum increase was recorded for Cu and Pb (by factors of 5–12 and 6–16, respectively); in fruits and berries, for Cd and Pb (by factors of 2–7 and 2–4); and in fungi, for Cd and Pb (by factors of 2–14 and 2–17). These values correspond to the factors of increase over the background levels of HMs in the food of bank voles during the same period.

Published data on long-term changes in the elemental composition of plants upon reduction of industrial emissions concern mainly the foliage of trees, whereas plants of the herb–dwarf shrub layer are poorly studied in this respect. The contents of HMs (Pb, Cd, Ni, Mn, Fe, Zn, Cu) in the assimilatory organs of conifers (spruce and pine) and deciduous trees (birch and oak) were found to decrease by a factor of 2 to 18 under such conditions, with the effect being more distinct in areas with an initially high pollution level [19, 34]. A decrease of similar magnitude (by a factor of 2 to 16) was observed in the concentrations of Cu and Ni in the leaves of dwarf shrubs (bilberry, cowberry, and blueberry) from the background and impact zones, while these concentrations in the

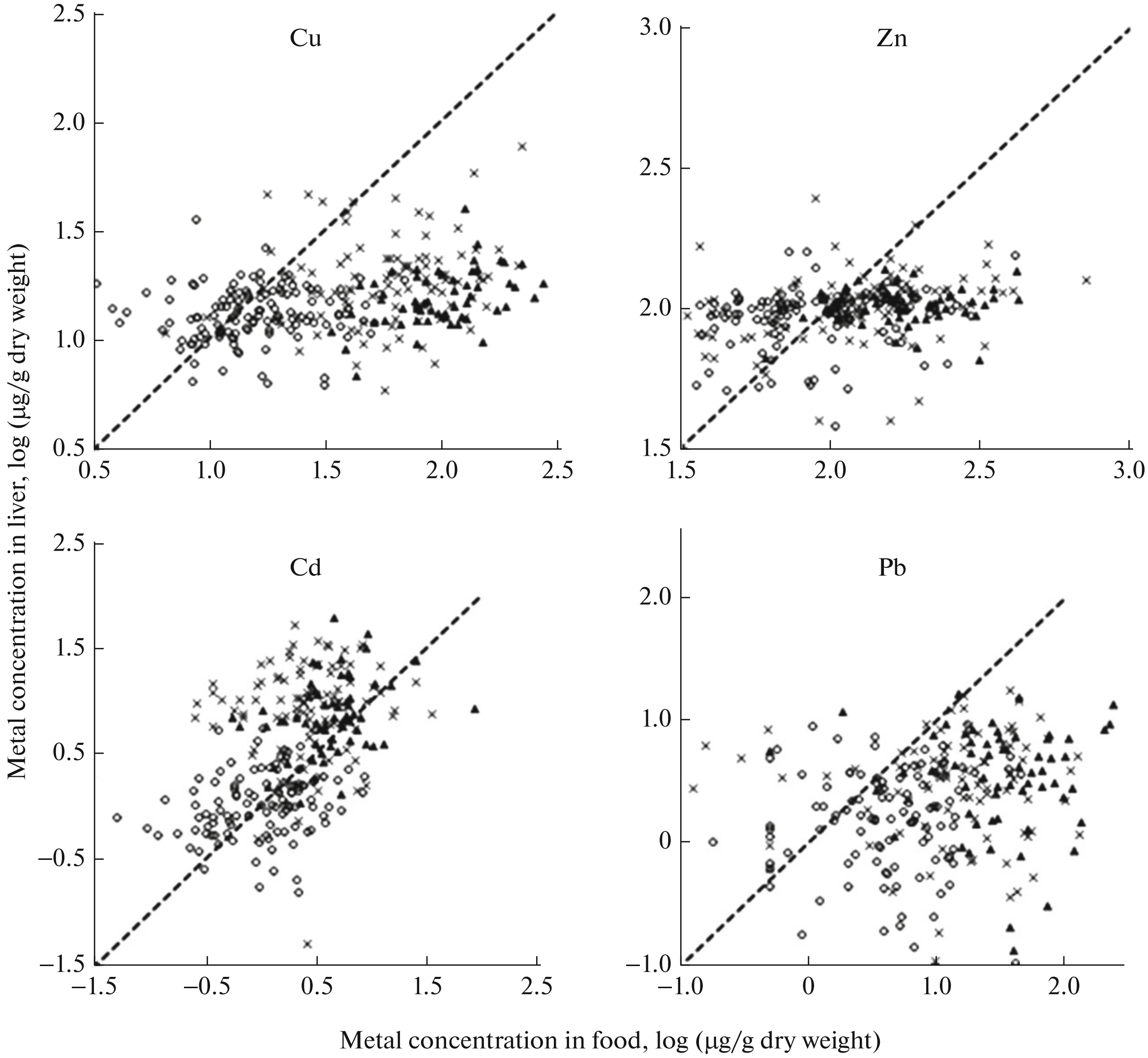

Fig. 3. Changes in heavy metal concentrations (μg/g dry weight, logarithmic values) in the food and liver of bank voles from zones with different pollution levels: (○) background plots, (×) buffer plots, (●) impact plots.

buffer zone remained unchanged or decreased only slightly [35]. The concentrations of Cd and Pb in mosses and lichens were also found to decrease but at a lower rate, by 30–70% relative to the initial level [5, 23].

Thus, dynamic changes in the contents of HMs in the food of voles from the vicinities of MUCS are manifested to a lesser extent than those observed in plants growing near other industrial pollution sources.

Dynamics of metal concentrations in the liver. Long-tern changes in the elemental composition of vertebrate tissues after reduction of industrial emissions are described in studies on small passerines (the pied flycatcher and great tit) from the vicinities of a Cu-Ni smelter in Harjavalta (Finland), a sulfide ore smelter in Rönnskär and a lead mine in Laisvall (Sweden). The response to decrease in emissions even in the same species, the pied flycatcher, was found to differ depending on particular conditions. Emissions from the Cu-Ni smelter were reduced by 95% over 18 years, and the concentrations of HMs (Cd, Pb, Ni, and Cu) in the liver of nestlings from its vicinities decreased by 58–95% relative to the initial values [24]. The concentration of Pb in the liver of nestlings from near the lead mine decreased by 35% within 25 years after the mine was closed [5]. On the other hand, 98% reduction of emissions from the sulfide ore smelter over 25 years did not result in an equivalent decrease in Pb and Cu concentrations in tissues: Pb concentration in the liver of nestlings decreased by only 9–15% [7]. According to the authors, the observed effect was so weak because of HM intake from the soil with food (ants), in which the contents of Cd, Cu, and Pb was increased by 10–40%.

We are not aware of such long-term studies on mammals, and available data on the dynamics of metals in the organs of rodents are contradictory. Thus, a study on wood mice from the site of the former Metaleurop Nord Pb-Zn smelter (northern France) showed that, 8 years after its closure, Pb concentrations in the liver and kidney of these animals decreased twofold, whereas Cd concentrations increased by a factor of 1.5–2 [8]. In southern Sweden, where 15-year monitoring revealed a considerable decrease in atmospheric deposition of Cd and Pb (by 20 and 70%, respectively), Cd concentration in the liver of bank voles decreased by a factor of 4.5–7.5, but no distinct trends in Pb concentration was revealed [23].

Oud data showed that significant reduction of Cu and Zn emission in the environment (by factors of 3000 and 15, respectively) had no effect on their contents in the lover of bank voles. This may be accounted for by the system of barriers maintaining body homeostasis [36]. One of these is the gastrointestinal barrier, which effectively protects from deleterious effects of various mechanical, chemical, and biological factors by means of their effective selective transport [37]. Its efficiency can be estimated from the plot of element concentration in the body as a function of its concentration in food: the bisector corresponds to direct proportionality between them, points below the bisector are indicative of element "discrimination" in the body, and points above the bisector, of its accumulation (see Fig. 3). Although the concentrations of dietary Cu, Zn, and Pb in the impact zone are high, their toxic load on the body is not significant due to the removal of excess HMs through the digestive tract. This barrier is less effective against Cd [38], and an increased Cd intake with food leads to its accumulation in the liver. Such a dependence has been described for small mammals of different trophic groups [39–41].

Thus, reduction of industrial missions may lead to differently directed changes in the elemental composition of vertebrate tissues. Then pattern of these changes is element-specific and may depend on different factors.

CONCLUSIONS

Although emissions from the MUCS were reduced dramatically over the past 25 years (1990–2015), no equivalent decrease in HM concentrations was revealed in the food and liver of bank voles from polluted areas: Cu, Zn, and Pb concentrations remains unchanged, whereas Cd concentrations increased twofold. The accumulation of Cd may be explained by increase in its contents in the soil and litter combined with normalization of soil pH, which provided for more active Cd uptake by herbaceous plants, the main food for bank voles. The concentrations of HMs in the food and liver of voles from the buffer zone showed no directional changes. In the background zone, the situation with Cu, Zn, and Cd was similar, whereas Pb concentration in the food and liver of voles decreased by a factor of 1.7–2.5, compared to the initial values. The main factors determining the level of HM accumulation in animals are the contents of HMs in food and, on the other hand, the system of element-specific homeostatic barriers (including the gastrointestinal barrier) that can effectively protect from the toxic action of HMs.

Thus, the results of this study do not confirm our hypothesis that the contents of HMs in the food and tissues of small mammals should gradually decrease after significant reduction of industrial emissions. The only exception is Pb, whose concentrations in the food and liver of bank voles has decreased significantly in the background zone.

Analysis of the long-term dynamics of HM concentrations was difficult because of their high variability. Sampling in stationary trap lines made it possible to reduce the spatial component of variation, but a mosaic pollution pattern in combination with multicomponent diet and high mobility of bank voles accounted for a high level of individual variation.

As emissions from the MUCS have ceased almost completely and ecosystems in its vicinities are gradually recovering [27, 42], it can be expected that the quality of habitats for small mammals (primarily foraging conditions) will improve within the next 5–10 years. This is likely to provide for an increase in animal abundance and formation of permanent bank vole colonies in the impact zone. Annual observations in small mammal communities confirm this hypothesis. As for the contents of HMs in food plants and animal tissues, they will probably remain high during the nest 20–30 years, since large amounts of these elements have been accumulated in the soil and litter.

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