

Red Fox *Vulpes vulpes* (L., 1758) as a Bioindicator of Mercury Contamination in Terrestrial Ecosystems of North-Western Poland

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Abstract In this study, we determined the concentrations of total mercury (Hg) in samples of liver, kidney and skeletal muscle of 27 red foxes *Vulpes vulpes* (L., 1758) from north-western Poland, and examined the morphometric characteristics of the collected specimens. The analysis also included the relationship between Hg concentration and the fox size, and the suitability of individual organs as bioindicators in indirect evaluation of environmental mercury contamination. Determination of Hg concentration was performed by atomic absorption spectroscopy. In the analysed samples, the Hg concentration was low and the maximum value did not exceed 0.85 mgHg/kg dry weight (dw). There were no significant differences in Hg concentrations in the analysed material between males and females or between immature and adult groups. The median concentrations of Hg in the liver, kidney and skeletal muscle were 0.22, 0.11 and 0.05 mgHg/kg dw, respectively. The correlation coefficients were significant between the concentrations of mercury in the liver, kidney and skeletal muscle (positive) and between the kidney Hg concentration and kidney mass (negative). Taking into account our results and findings of other authors, it may be argued that the red fox exhibits a measurable

response to mercury environmental pollution and meets the requirements of a bioindicator.

Keywords Red fox · Mercury · Liver · Kidney · Muscle · Biomonitoring

Introduction

Mercury is one of the most toxic trace metals. This element is used in many industries, including pharmaceutical and chlor-alkali manufacturing industries, electrical engineering, mining, metallurgy and agriculture. Annually, anthropogenic pollution reaches approximately 2,300 tonnes of this metal, most of which comes from burning coal, milling of nonferrous metals and gold mining by amalgamation [1–4]. In Europe, the majority of mercury emitted into the environment comes from the combustion of solid fuels, mainly coal (~47%), cement production (~13%), iron milling (~5%), zinc and lead milling (~7%) and incineration of waste (~5%) [5].

In Poland, mercury emission to the atmosphere has significantly decreased in recent years, for example in 2001, 2005 and 2007 it was about 23, 21 and 15.9 tonnes of mercury, respectively [6]. Yet Poland is still one of the European countries that emit the largest quantities of this metal.

Terrestrial vertebrate organisms, including wild animals, absorb mercury via food, water, air and through the skin. Organic mercury is strongly absorbed from the gastrointestinal tract (>90%) and accumulates in internal organs, mainly in the liver, kidney and also in the brain [7–9]. In contrast, elemental mercury and its inorganic compounds are very poorly absorbed in the gastrointestinal tract (<10%), and additionally their harmful effects on warm-blooded vertebrates, including man, is much lower than methylmercury (MeHg) which is widespread in the environment, especially in water ecosys-

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tems [10, 11]. Removal of mercury from mammalian organisms occurs through the digestive system (with biliary) and the urinary system [2, 8, 12, 13]. Neurotoxicity of mercury in mammals, including the effect of MeHg, has been well researched and documented [8, 9, 13–15].

The first reports on the toxic effects of mercury contamination on wild animals, including the fox (in particular foxes associated with agroecosystems), started to appear in 1950s to 1970s, when countries with highly industrialized agriculture were widely using organic mercury in chemicals for plant protection. Prey (e.g. rodents and passerines) and then predatory birds and mammals started to accumulate significant amounts of organic mercury by eating beans and small warm-blooded vertebrate herbivores contaminated with mercury. It was found that wild and laboratory mammals, due to the related damage in the central nervous system, particularly the cerebellum, exhibited awkward and jerky movements, walking in circles and falling down [10, 16, 17].

At present, in inland ecosystems very high concentrations of mercury can be found in liver and kidney (>20 mg/kg dry weight, dw), along with symptoms of sublethal and lethal mercury poisoning, mainly in piscivorous birds and mammals, the final consumers in aquatic trophic chains. In these chains, methylmercury is subject to biomagnification, confirmed by reports on mammals such as American mink *Neovison vison* (Schreber, 1777), river otter *Lontra canadensis* (Schreber, 1777) and Eurasian otter *Lutra lutra* (L., 1758) [13, 15, 18–20]. The bioaccumulation of mercury in vertebrates in inland aquatic ecosystems has been well documented, whereas much less is known about the impact of mercury on typical terrestrial organisms, including foxes and other canids [10, 12, 21–24].

The most widespread predator in the order Carnivora is the red fox *Vulpes vulpes* (L., 1758), occurring across an area of about 70 million square kilometres. It lives in almost the entire northern hemisphere, from the Arctic Circle to North Africa, Central America and the Asian steppes, with the exception of Iceland, the Arctic islands and parts of Siberia [25]. An omnivore with a very varied diet, the red fox easily accommodates to environmental conditions. The food of red foxes living in Poland consists mainly of small rodents, ungulate carcasses (about 58–60% and 25–30%), birds, and also invertebrates and plant parts [26]. In other areas of Europe, its diet may have different proportions. For example, as shown by Kauhala et al. [27], in coniferous forests of Finland the red fox mainly preys on rodents (>60% of the diet), followed by birds and hares (20%), and then invertebrates and plants (20%).

In this study, we determine total mercury concentrations in liver, kidney and skeletal muscle of red foxes coming from north-western Poland. We analyse the relationship between the concentration of mercury and selected biomet-

ric parameters, and also assess the usefulness of this species as an indirect bioindicator of mercury pollution.

Materials and Methods

Study Area

The research material was collected in 2004–2006 in north-western Poland, in the West Pomerania province with its capital, Szczecin (53°25'57"N, 14°33'19"E). Most of the province's area is agricultural (38%) and forested (35%), and several percent of the area is covered by water (numerous lakes, rivers, including the Oder estuary with the Dąbie Lake and the Szczecin Lagoon; http://www.stat.gov.pl/cps/rde/xbcr/szczec/ASSETS_przeegl_2.pdf). Areas from which the animals were obtained were about 10–20 km away from the centre of Szczecin.

In 2007, the total atmospheric emission of mercury in Poland was 15,880 kg. In the West Pomeranian Voivodeship, it was 515 kg, i.e. 3.2% of the Polish emission [6]. This administrative region has a moderate (II on the five-grade scale) degree of atmospheric emission of mercury. In Poland geochemical background for mercury is <0.05 mg/kg dw. In years 1995–2005 in north-western Poland, the mean arithmetic concentration of this metal in river and lake sediments was 0.372 and 0.142 mg/kg, respectively; therefore, it exceeded the level of the geochemical background [28]. In Poland, the average Hg concentration in soil estimated in 2003 was 0.036 mg/kg dw [29].

The analysis of the effect of environmental factors on metal concentrations in carnivores should take into account their prey. The fox diet in Poland is dominated by food of animal origin, up to >95% of eaten biomass; the share of rodents (mainly *Microtus*), dead animals (mostly ungulates) and birds are 59%, 27% and 9%, respectively [30]. Mercury concentrations are low in the bodies of hunted ungulates that are not associated with aquatic trophic chains. Falandysz and Szajek [31] detected only low mercury concentrations in the muscles of deer, roe-deer and wild boar near the city of Koszalin (eastern part of the West Pomeranian voivodeship) 0.014, 0.007 and 0.023 mg/kg dw, respectively. Many times higher concentrations of mercury were found in the muscles of ducks from north-western Poland. Depending on their diet, it was 0.114 and 2.347 mg/kg dw, respectively, for in the omnivorous mallard *Anas platyrhynchos* (L., 1758) and piscivorous goosander *Mergus merganser* (L., 1758) [32, 33].

Biometrics and Sampling

Among the 27 red foxes *Vulpes vulpes* (L., 1758) collected for testing, most were hunted (18) but some dead specimens

(9) were collected from roads, mostly within the Szczecin city limits. During post-mortem examination, the sex of foxes was identified on the basis of observed gonads. Age classification into adult and immature specimens was based on linear measurements of prepared skulls [34], and in some specimens on annual growth layers in fangs [35, 36]. Individuals younger than 10 months were termed immature, while those older than 1 year were classified as adult. The adult group included 7 males and 4 females, and the immature group had 14 males and 2 females.

All foxes were weighed and measured (precision of measurements is given in parentheses). The measurements included the weights of the body (including skin, precision to 100 g), liver and kidney (0.1 g) and the lengths of the body (from the nasolabial plate to the tail, 1 cm), left foot (1 mm) and the height of the left ear (1 mm). In addition, we also calculated the relative weight of both liver and kidney, as the percentage of body weight.

For chemical analysis, from each individual we collected pieces of liver, thigh muscle and kidney (left or right)—a total of 81 samples, each weighing at least 0.1 g. Within 50–60 days the samples were dried to constant weight at 50°C. This allowed determination of the percentage of water content by gravimetric method. Then the dried material was ground in a monoplanetary Pulverisette mill. This procedure was consistent with that used by other researchers [24].

Determination of Total Mercury

The accuracy and precision of the analytical procedure was maintained by the determination of Hg concentration in two certified biological materials: lyophilized bovine liver (BCR 185; 0.04 mg/kg dw) and lyophilized porcine kidney (BCR 186; 1.73 mg/kg dw; Commission of European Communities, Community Bureau of References—BCR). The percentage of recovery was 99.3% and 88%, respectively.

The concentration of total Hg was determined by atomic absorption spectroscopy, using an AMA 254 mercury analyzer (Altec, Czech Republic). This device does not require prior digestion of the wet sample, as a dry sample is placed directly in a nickel nacelle. The detector in the AMA 254 analyzer is a silicon UV diode operating at 254 nm, in a system of two measuring cells. The samples were analysed at specified parameters of the cycle: 60/160/60, which means the time of drying (in seconds), time of decomposition (at 550°C) and waiting time for the measurement. The mercury detection limit for this device is about 0.01 ng. For each sample, two or three repetitions were performed, and the averaged result was presented as the concentrations in milligrammes per kilogramme of dry weight (mg/kg dw).

Statistical Analysis

Percentage water content was calculated in the analysed samples of biological material. Arithmetic mean and standard deviation (AM±SD) were established for the sizes of animals and their organs. For body and organ sizes, the AM±SD were calculated. In order to compare morphological parameters between age groups and sexes, a Student *t* test was used. Pearson correlation coefficients were calculated in order to investigate possible correlations between the weights of the body, liver and kidney.

Median (Med), AM±SD and percentage coefficient of variation were calculated for Hg concentrations in the liver, kidney and muscle. In order to determine compliance with the expected normal distribution of results, Shapiro–Wilk test was used ($p < 0.05$) for raw data and data subjected to logarithmic transformation (\log_{10}). In order to analyse related differences between Hg concentrations in the tissues (liver, kidney, muscle), a Kruskal–Wallis test was applied ($p < 0.05$); for age and sex comparisons of Hg levels in analogical tissues, a Mann–Whitney *U* test was used. The strengths of relationships between Hg concentrations in the examined biological materials were estimated using a Spearman's correlation coefficient (r_s , $p < 0.05$ and $p < 0.001$), while a Pearson's correlation coefficient was calculated for relationships between organ weight and Hg level. Statistical analysis was performed using Statistica 8.0 software.

Results

Fox Morphometry

Fox body weights ranged from 2,700 to 8,600 g (Table 1). Immature specimens weighed approximately 1,000 g less than adults, and females about 700 g less than males, however, these differences were not statistically significant ($p > 0.05$). Foot length in males was about 8 mm longer than in females ($p < 0.01$). Immature differed from adult in the weight of liver and kidney ($p < 0.05$); they were smaller by 24% and about 17%, respectively. Liver weight was about 140 g on average and weighed 4.5 times more than the kidney. The relative weights of liver and kidney did not differ between females and males and between immature and adult. These organs in the whole group accounted for 2.6% and 0.6% of body weight.

The Concentration of Mercury in Biological Samples

In samples from the examined 27 foxes, the average percentage of water content in the liver, kidney and skeletal muscle of the fox was 70.1%, 72.5% and 73.3%,

Table 1 The body dimensions as well as organ relative weights of the red fox from north-western Poland

Age or sex group, the number of individuals in each group (n) and parameters	Body dimensions				Organ dimensions				
	Weight, BW (g)	Length (cm)	Foot length (mm)	Ear height (mm)	Absolute (g)		Relative (%)		
					Liver (L)	Kidney (K)	L/BW	K/BW	
im (n=16)	AM±SD	5,387±924	65±7	158±7	84±8	131±35*	30±6*	2.5±0.6	0.6±0.1
	Min-max	3,700–7,200	50–76	148–170	71–100	71–210	22–42	1.3–3.8	0.4–0.7
ad (n=11)	AM±SD	6,018±1,126	68±5	158±7	85±9	162±32*	35±5*	2.8±0.7	0.6±0.1
	Min-max	4,900–8,600	61–78	150–175	72–100	115–204	25–43	1.6–3.6	0.5±0.7
M (n=21)	AM±SD	5,800±1,123	67±7	160±6**	86±8	145±36	33±6	2.6±0.7	0.6±0.1
	Min-max	3,700–8,600	50–78	148–175	71–100	71–210	24–43	1.3–1.8	0.4–0.7
F (n=6)	AM±SD	5,100±335	65±2	152±3**	81±6	140±40	29±6	2.7±0.7	0.6±0.1
	Min-max	4,700–5,600	61–67	150–155	72–90	102–204	22–36	2.1–3.6	0.4–0.7
Total (n=27)	AM±SD	5,644±1,039	66±6	158±7	85±8	144±37	32±6	2.6±0.7	0.6±0.1
	Min-max	3,700–8,600	50–78	148–175	71–100	71–210	22–43	0.7–1.2	0.4–0.7

im immature, ad adult, M male, F female, AM arithmetic mean, SD standard deviation

* $p < 0.05$ statistical difference; ** $p < 0.01$ statistical difference

respectively. Data on mercury concentrations in liver, kidney and muscle of the fox age groups and gender are shown in Table 2. The distribution of empirical data on mercury concentrations in the liver, kidney and skeletal muscle diverged from the expected normal distribution, as

shown by the Shapiro–Wilk test ($p < 0.05$). After logarithmic transformation (\log_{10}), hepatic and nephric Hg concentration distributions were consistent with the expected normal distribution (Shapiro–Wilk test, $p > 0.05$), but the muscle concentration distribution still differed from

Table 2 Total of mercury concentration in the liver, kidney and skeletal muscle (milligrammes per kilogramme dry weight) in the red fox from north-western Poland

Age or sex group, the number of individuals in each group (n) and parameters	Liver	Kidney	Muscle
im (n=16)	Med	0.10	0.05
	Q _L –Q _U	0.08–0.17	0.03–0.07
	AM±SD	0.13±0.09	0.06±0.04
	Min-max	0.04–0.37	0.02–0.19
ad (n=11)	Med	0.11	0.05
	Q _L –Q _U	0.08–0.16	0.04–0.06
	AM±SD	0.15±0.13	0.08±0.06
	Min-max	0.08–0.52	0.03–0.23
M (n=21)	Med	0.11	0.05
	Q _L –Q _U	0.08–0.16	0.04–0.06
	AM±SD	0.14±0.08	0.06±0.04
	Min-max	0.04–0.37	0.03–0.19
F (n=6)	Med	0.10	0.05
	Q _L –Q _U	0.07–0.12	0.03–0.05
	AM±SD	0.16±0.18	0.07±0.08
	Min-max	0.05–0.52	0.02–0.23
Total (n=27)	Med	0.11	0.05
	Q _L –Q _U	0.08–0.16	0.04–0.06
	AM±SD	0.14±0.10	0.07±0.05
	Min-max	0.04–0.52	0.02–0.24

im immature, ad adult, M male, F female, Med median, Q_L lower, Q_U upper quartile, AM arithmetic mean, SD standard deviation

one another (Shapiro–Wilk, $p < 0.05$). Median concentrations (Med) of Hg in the liver, kidney and skeletal muscle were small and generally did not exceed 0.30 mg/kg dw. The highest concentrations of Hg were recorded in the kidney and the smallest in the skeletal muscle (0.84 and 0.02 mg/kg dw, respectively). Therefore, median values of Hg concentrations can be arranged in the following series: kidney > liver > skeletal muscle, with the ratio of 4:2:1. This observation concerned all the groups (Mann–Whitney U test, $p < 0.05$). The Kruskal–Wallis test showed a difference in Hg concentrations between skeletal muscle and liver ($p < 0.01$), skeletal muscle and kidney ($p < 0.0001$) and between the Hg concentrations in liver and kidney ($p < 0.01$). Comparison of Hg concentrations in with regard to age (immature and adult) and sex (female and male) showed no statistically significant differences (Mann–Whitney U test, $p > 0.05$).

Analysis of Spearman correlation coefficients (r_s) showed that the strongest relationship existed between Hg–liver and Hg–skeletal muscle ($r_s = 0.74$; $p < 0.001$), and weaker relationships existed between Hg–kidney and Hg–liver ($r_s = 0.60$; $p < 0.001$), and between Hg–kidney and Hg–skeletal muscle ($r_s = 0.57$; $p < 0.01$). The relationship between the mass of kidney and Hg concentration was negative and statistically significant ($r = -0.50$; $p < 0.02$). This correlation coefficient suggests that the increasing concentration of nephric Hg is accompanied by a lower mass of kidney.

Discussion

Ecotoxicological studies on the prevalence of toxic metals and other xenobiotics in the terrestrial environment include the measurements of their concentrations in the tissues of birds and mammals. Among mammals, primarily herbivorous ungulates are deemed good indicators of pollution: fallow deer *Dama dama* (L., 1758), red deer *Cervus elaphus* (L., 1758), moose *Alces alces* (L., 1758) and the omnivorous wild boar *Sus scrofa* (L., 1758), but they are not represented outside their natural habitats and areas of incidence [37–41]. Furthermore, the home ranges of the individuals of those species are very large, which hinders the determination of sources of pollution [42]. In contrast to the aforementioned ungulates, the fox easily adapts to a wide range of environments, including urban areas, and occupies small territories with an average home range of 0.5 km² [25].

Although there were some reports of red foxes that were ten or so years old, their average lifespan is much shorter [25, 43, 44]. It is estimated that most foxes die in the first months and years of their lives, as reflected in the age structure of specimens collected for this study, where out of

27 foxes, 16 (~60%) were classified as immature. The average body and kidney weights in foxes from NW Poland did not deviate from those observed in an Italian population examined by Cavallini [45], although what differed was the average weight of livers, which was 12% higher. Cavallini [45] points out that data on the morphometry of the free-living red fox, i.e. on the body (except for weight and length) and internal organs including the liver and kidney, are rarely published in Europe and other parts of the world, so our data may be deemed complementary in this regard.

In mammals, mercury is determined mostly in the liver and kidney which perform detoxification functions. Although there are already a few reports on mercury in red fox, there has not been established the mercury threshold value for this mammal (above which adverse changes occur). Such information is available for the domestic dog *Canis lupus familiaris* L. 1758 which also belongs to the family Canidae. The laboratory tests conducted on the dog show that the typical concentration of mercury (reflecting the geochemical background) in the liver and kidney is <0.1 mg/kg wet weight, ww (~0.3 mg/kg dw), while 2.8 and 3.3 mgHg/kg ww are considered lethal (9.3 and 11 mgHg/kg dw) [46]. In general, dogs usually have small amounts of mercury in their livers and kidneys, for example dogs studied in Spain had 0.032 and 0.053 mg/kg ww, respectively and it was proved that higher amounts of mercury were accumulating in kidney (but not the liver) of dogs from urban areas than from rural areas [47]. Bilandzic et al. [48] well documented an influence of suburban and rural habitats on mercury accumulation in Croatian red foxes. They found higher levels of hepatic and nephric mercury concentrations in suburban red foxes than in rural areas.

The accumulation of considerable amounts of mercury in canines depends very much on their diet, especially when it is rich in fish, as documented in several cases [24, 49]. However, mercury poisoning in this group of wild mammals is very rare. One known case was observed in a Swedish wild fox with Hg poisoning symptoms—running around, staggering, apparently blind without olfactory sense. A mixed sample from the liver and kidney from that individual contained 30 mg Hg/kg ww [16]. Later, starting from the 1980s, neither red fox nor Arctic fox *Vulpes lagopus* (L., 1758) were observed to have nephric and hepatic Hg concentrations higher than 10 mg/kg dw, which corresponds to ~2.5 mgHg/kg ww (Table 3).

In recent years, the highest Hg concentrations in the liver and kidney of the red fox ranged from about 4.2 to 5.4 mgHg/kg dw and were observed only in single individuals in Poland and Spain (Table 3). In both cases, the considerable Hg concentrations were due to unusual environmental conditions and diet. The red foxes on the small island of Mielin in Poland (West Pomerania the Oder

Table 3 Comparison of total Hg concentrations (microgrammes per kilogramme) in dry weight (dw) and wet weight (ww) in foxes from various parts of the world

Species	Number (n)	Mean, Min-Max	Dry weight or wet weight (dw or ww)	Liver	Kidney	Muscle	Place	Source
Silver fox <i>Vulpes vulpes</i> f. domestica (L., 1758)	30	M	ww	0.023	0.014		Poland, Lublin region (breeding farm)	[51]
		Min-max		0.007–1.158	0.006–3.695			
Wild red fox <i>Vulpes vulpes</i> (L., 1758)	7	M	dw	(0.082)	(0.056)		Poland, Zachodniopomorskie province	[24]
		GM	dw	0.12	0.23	0.05		
	3	Min-max	ww	0.04–0.52	0.09–0.84	0.05–0.23		
		GM	dw	(0.03)	(0.06)	(0.02)	Mielin Island	[24]
	18	GM	dw	4.51	5.11	3.01		
		Min-max	ww	4.22–4.89	5.06–5.14	2.23–3.66		
16	GM	dw	(1.26)	(1.28)	(0.77)			
	AM±SD	ww	0.22±0.23	0.63±0.51	0.013±0.019	Slovakia, Zemplin	[40]	
12	Min-max	dw	0.03–0.62	0.06–1.43	0.006–0.090			
	AM	dw	(0.81±0.82)	(2.33±1.89)	(0.04±0.07)			
16	GM	dw	0.393		0.161	Spain, Donana	[23]	
	Min-max	ww	ND-5.36		ND-1.769			
12	GM	ww	(0.283)		(0.120)			
	AM±SE	ww	0.025±0.008	0.064±0.017	0.007±0.02	Croatia, suburban areas of Zagreb and Varazdin (2008–2009)	[48]	
16	Min-max	dw	0.003–0.080	0.007–0.164	0.0008–0.020			
	AM	dw	(0.089)	(0.256)	(0.029)			
5	AM±SE	ww	0.009±0.02	0.032±0.005	0.004±0.0007	Croatia, rural areas in Hrvatsko Zagorje region (2008–2009)	[48]	
	Min-max	dw	0.004–0.027	0.001–0.078	0.0006–0.011			
46	AM	dw	(0.032)	(0.128)	(0.016)	Italy, Urbino-Pesaro	[53]	
	AM±SE	ww	0.03±0.01					
12	Min-max	dw	ND-0.62					
	AM	dw	(0.11)					
3	AM±SD	dw	0.16±0.14			Italy, Siena (1992)	[52]	
	AM	ww	(0.04)					
2	AM	ww	0.04	0.14	0.02	U.S., Wisconsin (1972–1975)	[57]	
	AM	dw	(0.14)	(0.52)	(0.07)			
93	AM	ww	0.38		0.11	Canada, N Quebec (1981–1990)	[58]	
	AM	dw	(1.41)		(0.41)			
2	AM	ww	0.41		0.22	Canada, N Quebec (1991–1997)	[58]	
	AM	dw	(1.52)		(0.82)			
93	AM±SD	ww	0.37±0.43			Norway, Svalbard (1984–1986)	[54]	
	Min-max	dw	0.01–2.2					
2	AM±SD	dw	(1.37±1.59)					
	AM	ww	0.25			Canada, N Quebec (1981–1990)	[58]	
13	AM	dw	(0.93)					
	AM±SE	ww	0.85±0.22			Canada, Ulukhaqtuq	[55]	

Table 3 (continued)

Species	Number (n)	Mean, Min-Max	Dry weight or wet weight (dw or ww)	Liver	Kidney	Muscle	Place	Source
	50	AM±SE	dw	(3.15±0.82)			Canada, Arivat	[55]
		AM±SD	ww	0.77±0.25				
		AM±SD	dw	(2.85±0.93)				
	26	AM±SD	ww	0.25±0.25	0.43±0.46		U.S., Alaska	[56]
		Min-max	dw	0.02–1.26	0.03–2.29			
		AM±SD		(0.93±0.93)	(1.59±1.70)			
	19	AM±SD	ww	0.32±0.42			Canada, Holman	[56]
		Min-max		<0.01–1.85				
		AM±SD	dw	(1.18±1.58)				

In conversions of the ww into dw, it was assumed that the water content in the liver, kidney and muscles is 72%, 75% and 74.5%, respectively
 ND not detected, AM arithmetic mean, GM geometric mean, SD standard deviation, SE standard error, M median

estuary), mainly fed on fish and dead cormorant chicks *Palacrocorax carbo* (L., 1758), which very strongly connected them with the aqueous food chain [24]. Spanish red foxes in the Donana National Park ate food (mainly rodents) contaminated with heavy metals, including mercury, because the area had been flooded by water from mines [23, 50].

In the examined foxes from north-western Poland, the median concentrations of Hg in the kidney, liver and muscle were low (0.22, 0.11 and 0.05 mg/kg dw, respectively) and very close to values determined in foxes ($n=7$) in the same area [24] (Table 3). With respect to kidney and liver it can be considered that these values reflect the geochemical background, as suggested by Farrar et al. [46]. However, when compared with the nephric and hepatic Hg concentrations given by Cybulski et al. [51] for the farmed silver fox (*V. vulpes* f. domestica; 0.056 and 0.082 mg/kg dw, respectively), red foxes in this study had about 290% higher concentrations of mercury in the kidney and 30% higher in liver. Also in the liver of red foxes from other European countries (Spain, Italy, Croatia and Slovakia), mercury concentrations were higher than in the silver fox, which is probably related to differences in diets of domesticated and wild specimens of this species and the degree of Hg environmental pollution. Similar values to the average Hg concentration in the liver of the fox in north-western Poland are reported for a population inhabiting Italy [52, 53] and suburban areas in Croatia [48]. In Slovakia, in studies on foxes living in areas with significant heavy metal contamination, nephric and hepatic Hg concentrations in the red fox were ~6–9 times higher than in foxes of the north-western Poland in this study, while concentrations of mercury in the muscles of both populations were similar (Table 3).

Some works on mercury in canids include analyses of age- and sex-related differences in the Hg concentrations. In farmed red foxes from Poland, wild red foxes from Poland and Spain, the Arctic fox from Norway and the dog in Spain, there were no statistically significant differences between different age groups in relation to hepatic Hg concentrations, and in the red fox from Poland and dog from Spain with respect to nephric Hg [23, 47, 51, 54, this study]. Hepatic and nephric Hg concentrations did not differ between males and females of the Polish red fox and Spanish dog [47, this study]. However, Millan et al. [23] noted a greater concentration of Hg in muscles of adult foxes compared to cubs (<1 month). In foxes in Poland, no differences were found in mercury content in muscles of both sexes and compared between age groups (immature and adult), but all specimens examined by us were over the age of 6 months.

In comparison with the Arctic fox (both from Norway and North America), Hg concentrations in the livers of the

European red fox from non-contaminated or slightly polluted areas were lower, and the differences between the species may have resulted from different diets, a higher share of fish in the Arctic fox, especially in coastal areas, geological background, and the different level of Hg environmental pollution [54–56].

Red fox is a species with a wide geographical range, occurring for the entire year in a small home range. It has a high position in the trophic pyramid and accumulates various xenobiotics, including Hg. Taking into account our results and findings of other authors, it may be argued that the fox exhibits a measurable response to environmental Hg pollution and meets the requirements for bioindicators [23, 24, 42, 48, 52, 53]. Thanks to the collection of data on the mercury concentration in fox liver and kidney, it is possible to make comparisons not only between European countries but entire continents (e.g. Europe and North America). That is why it seems justified to research the degree of Hg contamination of typical inland ecosystems with the widest use of the fox as a bioindicator.

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