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AQUATIC TOXICOLOGY

Mercury in the Muscle Tissue of Fish in the Central and South Vietnam

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Abstract—The content of mercury has been determined in the muscle tissue of 18 fish species in rivers, lakes, and reservoirs of Central and South Vietnam. The region is characterized by lower metal concentrations than those in water bodies in temperate and northern latitudes. In 76% of samples ($n = 986$), the content of Hg was ≤0.5 μg Hg/g of dry (≤0.1 μg/g of wet) tissue weight. In water bodies and watercourses of tropical latitudes, interspecific variations in fish can be one of the factors responsible for a wide range of Hg variation within the same species.

Keywords: mercury, fish, tropical ecosystems, Vietnam, Southeast Asia

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INTRODUCTION

The industrial age is characterized by active human utilization of mineral resources, which results in changes in global and regional cycles of many chemical elements. The volume of anthropogenic Hg emission is comparable to the amount of metal entering the environment from natural sources [28]. The unique physicochemical properties of Hg determine the features of its concentration and redistribution in different environmental components, and the diversity of forms determines the specific nature of its migration and transformation under natural and technogenic conditions [29, 32]. Unlike other heavy metals, it can effectively accumulate in food chains of water ecosystems, thereby having a wide and various range of negative effects on living organisms, their populations, and ecosystems in general [3, 13, 34].

There is a large amount of factual material on the levels of metal content and regularities of metal migration in water bodies of temperate latitudes, which is historically due to a high concentration of industrial facilities on these territories [25]. However, over the last 30 years, the focus of technogenic metal emission has been shifted towards the region of Asia. This dynamically developing area, with the highest population density in the world, generates no less than 60% of all anthropogenic Hg emissions [21, 28]. Although there is evidence of global spatial disproportion of Hg entry to the environment, the amount of data on its content in components of ecosystems of Southeast Asia is limited [1, 2].

The objective of this work is to study the regional features of levels of Hg content in the muscle tissue of fish in water bodies of different types in Central and South Vietnam.

MATERIAL AND METHODS OF RESEARCH

The studies were carried out in rivers, lakes, and reservoirs located in six Vietnamese provinces (Fig. 1). This area is characterized by a tropical monsoon climate with clearly pronounced dry and wet seasons. The average precipitation varies from 1600 to 2500 mm/year; the temperature varies from 22 to 30°C [7].

The banks of all the investigated water bodies are densely populated and are of great domestic importance, being utilized for drinking water supply, agricultural field irrigation, and fishery.

Freshly caught fish for analysis were obtained from fishermen living near the water bodies and then packed in thermal containers and transported at a temperature of ≤5°C. If there was no possibility to deliver the material to the laboratory within 8 h, the fish was frozen and transported at a temperature of not more than –15°C. The biometric analysis was then carried out under stationary conditions, followed by the separation of 5 g of muscle tissue from the dorsal part of body below the dorsal fin using tools made of surgical steel. The samples were dried using the method of convection at a temperature of 30–35°C and stored in a fridge at a temperature of 5°C in sealed containers before analysis.

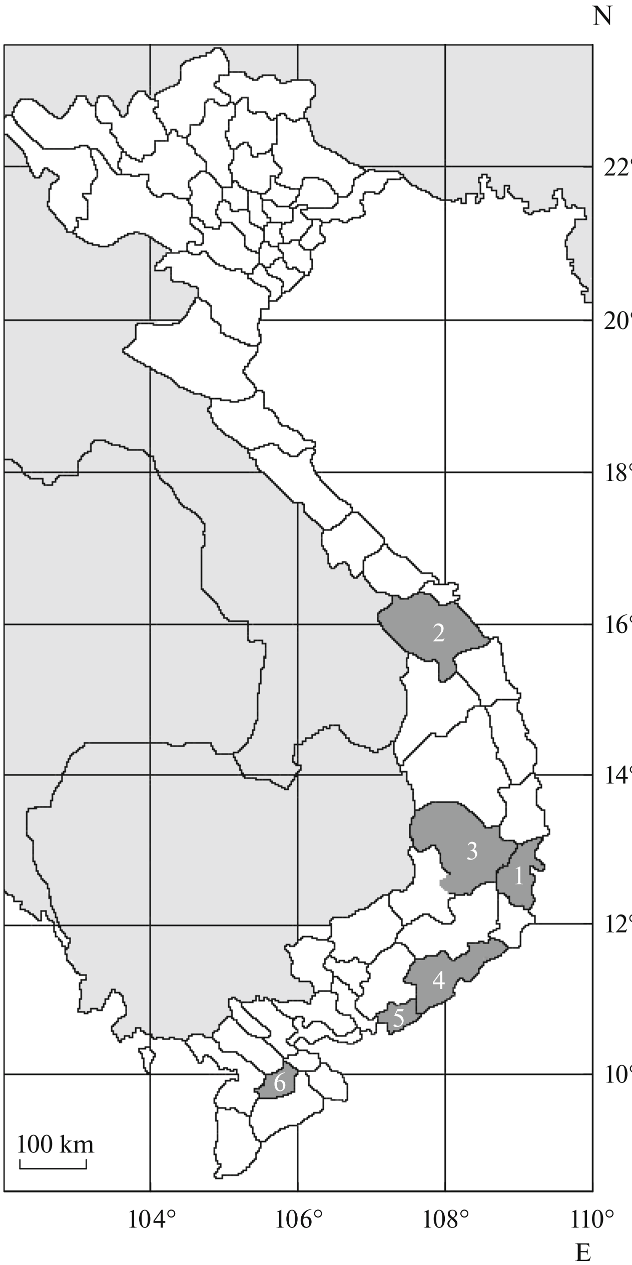

Fig. 1. Map of the study area. Provinces: (1) Khánh Hòa, (2) Quảng Nam, (3) Đắk Lak, (4) Bình Thuận, (5) Bà Rịa-Vũng Tàu, and (6) Can Tho (Mekong River delta).

The total Hg concentration in the muscle tissue of fish was measured by the method of flameless atomic absorption with a Zeeman correction of nonselective absorption using a PA-915$^+$ mercury analyzer with a PIRO-915$^+$ attachment (Lumex, Russia) [2]. The detection limit was 0.005 μg Hg/g. The accuracy of analytical measuring methods and the reliability of data allowed for permanently monitoring the quality of results of analysis using international certified standard samples made of shark liver tissues and muscles (DOLT-2 and DORM-2). The difference between the defined and certified values was ±2%. The reproducibility of results of analysis in the parallel series of measurements is ±1%.

Eighteen fish species were investigated: *Anabas testudineus* (Bloch), *Bagarius yarelli* (Sykes), *Channa gachua* (Hamilton), *Channa striata* (Bloch), *Clarias batrachus* (L.), *Clarias fuscus* (Lacepède), *Clarias macrocephalus* (Günther), *Mastacembelus armatus* (Lacepède), *Misgurnus* sp., *Monopterus albus* (Zuiew), *Mystacoleucus marginatus* (Valenciennes), *Mystus* sp., *Notopterus notopterus* (Pallas), *Ompok bimaculatus* (Bloch), *Oreochromis niloticus* (L.), *Osteochilus vittatus* (Valenciennes), *Puntius* sp., and *Xenentodont cancila* (Hamilton).

A total of 986 muscle tissue samples were studied. The results were statistically processed and presented in the form of mean values and their errors and minimum and maximum values. The significance of differences was assessed using the analysis of variance method (ANOVA and LSD-test) at a significance level of $p \le 0.05$.

RESULTS OF RESEARCH

Khánh Hòa Province. In the Cái River, the maximum mean values of Hg were recorded in freshwater garfish (*Xenentodon cancila*) and walking catfish (*Clarias batrachus*), while the minimum mean values were recorded in Nile tilapia (*Oreochromis niloticus*) and barbel (*Mystacoleucus marginatus*) (Table 1). In samples of freshwater catfish and garfish, the Hg concentration was more than 2 μg/g in 18.3% and 10.3% of individuals, respectively; single specimens of *Clarias batrachus* contained more than 3 μg/g.

A high interspecific range of values was recorded in all the investigated fish from the Cái River. For example, the mercury concentration varied from 0.07 to 1.9 μg/g of muscle tissue in *Channa striata* with a weight of less than 100 g, from 0.07 to 1.48 μg/g of muscle tissue in fish with a weight from 100 to 200 g, and from 0.24 to 1.8 μg/g of muscle tissue in muscle with a weight of more than 200 g. The mean values did not have significant differences for any weight groups: 0.54 ± 0.06, 0.48 ± 0.07, and 0.68 ± 0.2 μg/g, respectively.

A significant positive correlation between weight and mercury concentration in fish was revealed for 5 of 12 fish species living in the Cái River. However, no analogical relationship was established in the same species from Cam Thuong and Suối Trầu reservoirs (Table 1).

Differences in metal content were established for some fish species in the upper and lower reaches of the Cái River. The fish of *Anabas testudineus* and *Clarias batrachus* in the lower reaches were larger and had higher Hg concentrations in the muscle tissue. A reverse trend was established for *Channa gachua*. In

Table 1. Mercury concentration in the muscle tissue of fish from water bodies of the Khánh Hòa province

Species	*n*	Weight, g	Length, cm	Hg, µg/g	R^2
			Cái River		
Herbivorous					
Mystacoleucus marginatus	4	201.8 ± 88.2 / 72–450	18.4 ± 1.9 / 15–23	0.13 ± 0.03 / 0.05–0.2	–
Oreochromis niloticus	22	98.9 ± 13.8 / 43–336	13.9 ± 0.5 / 10.5–22	0.043 ± 0.004 / 0.013–0.1	**0.51**
Plankton feeders					
Osteochilus vittatus	16	72.9 ± 8.2 / 38–150	13.5 ± 0.5 / 11–17	0.37 ± 0.05 / 0.22–0.82	0.08
Puntius sp.	10	51.2 ± 9.0 / 29–129	12.2 ± 0.5 / 10.3–16	0.45 ± 0.1 / 0.21–1.23	0.17
Predators					
Channa gachua	36	113.6 ± 22.2 / 11–584	17.5 ± 1.0 / 9.0–35	0.6 ± 0.04 / 0.082–1.19	–0.08
C. striata	79	114.8 ± 9.4 / 30–465	20.3 ± 0.6 / 12–40	0.55 ± 0.045 / 0.069–1.91	0.13
Monopterus albus	22	68.6 ± 5.2 / 31–130	41.1 ± 1.04 / 34–51	0.18 ± 0.04 / 0.039–0.81	0.35
Notopterus notopterus	44	68.4 ± 5.2 / 10–131	18.4 ± 0.5 / 12–23	0.56 ± 0.055 / 0.17–1.84	**0.47**
Ompok bimaculatus	27	25.5 ± 2.4 / 10–56	13.1 ± 0.4 / 10–17	0.72 ± 0.06 / 0.24–1.58	0.39
Xenentodont cancila	29	18.1 ± 1.6 / 9–44	19.1 ± 0.6 / 15–25	1.31 ± 0.081 / 0.23–2.33	0.32
Omnivorous					
Anabas testudineus	37	18.4 ± 1.4 / 10–46	7.9 ± 0.18 / 6–11	0.18 ± 0.02 / 0.047–0.54	**0.58**
Clarias batrachus	71	138.5 ± 13.9 / 28–520	22.4 ± 0.7 / 12–45	1.1 ± 0.11 / 0.12–3.26	**0.82**
			Cam Thuong Reservoir		
Herbivorous					
Oreochromis niloticus	25	109 ± 10.1 / 52–184	13.9 ± 0.35 / 12–18	0.13 ± 0.007 / 0.02–0.19	–0.14
Predators					
Channa striata	10	315.7 ± 80.8 / 71–860	26.3 ± 2.2 / 18–40	1.26 ± 0.22 / 0.083–1.93	0.11
Notopterus notopterus	36	87 ± 5.6 / 40–174	19.8 ± 0.4 / 16–23	0.55 ± 0.054 / 0.24–1.84	0.18
Xenentodont cancila	7	23.9 ± 3.2 / 8–36	20.8 ± 1.0 / 15–24	0.77 ± 0.21 / 0.33–1.85	0.68
Omnivorous					

Table 1. (Contd.)

Species	n	Weight, g	Length, cm	Hg, μg/g	R^2
Anabas testudineus	15	14.1 ± 1.8 7–35	7.5 ± 0.3 6–10	0.29 ± 0.02 0.2–0.44	–0.27
Clarias batrachus	2	311.5	27.1	0.37	–
			Suôi Trâu Reservoir		
Predators					
Channa striata	25	174.1 ± 15.5 75–415	22.3 ± 0.7 17–31	0.39 ± 0.066 0.13–1.29	0.04
Omnivorous					
Clarias batrachus	3	264.3 ± 72.1 120–337	27.8 ± 3.4 21–32	0.076 ± 0.042 0.03–0.16	–

Here and in the Tables 2 and 3, n is the number of fish, samples; the mean value and its error are given above the line and the minimum and maximum values are given below the line; and R^2 is the coefficient of paired correlation between Hg and fish weight. The values meeting the 95% level of significance are given in bold.

the lower reaches, the individuals were larger; however, they had a significantly lower amount of Hg than that found in samples from the upper reaches of the river. A different picture was observed in a closely related species, *C. striata*. The metal concentration was 2.7 times higher in the individuals from the upper reaches than that in the individuals from the lower reaches with the same values of body weight and length (0.81 ± 0.07 and 0.31 ± 0.03 μg Hg/g, respectively).

The ranking of species in the Cam Thuong Reservoir with respect to the level of Hg content had some differences from that in the other two water bodies (Table 1). The maximum concentrations were found in snakehead *C. striata*, while the minimum concentrations were recorded in Nile tilapia *Oreochromis niloticus*. The content of Hg in their muscle tissue was 2–3 times higher than that in the same species caught in the river. A typical representative of the ichthyofauna of the investigated region is snakehead *Channa striata*, which occupies a high position in the food web of rivers and reservoirs. A comparison of the data on Hg concentration in snakehead muscles from the three water bodies shows that the highest metal content is characteristic of individuals from the Cam Thuong reservoir, while the lowest content is characteristic of individuals from the Su'ôi Trầu Reservoir; the individuals from the Cái River occupy the intermediate position (Table 1).

Quảng Nam Province. The fish from three rivers of this province are characterized by small interspecific differences in metal content (Table 2). The maximum values were recorded for *Mastacembelus armatus*, while the minimum values were found in *Oreochromis niloticus* from the Tranh River. It should be noted that *Anabas testudineus* and *Bagarius yarrelli* species from this river have the same average concentration of Hg in the muscle tissue (0.35 μg/g), although they have significantly different size and weight characteristics. We did not find any correlation dependences between the weight of fish and the mercury concentration in any of the species under consideration (Table 2).

Đắk Lak Province. Maximum interspecific differences in Hg concentration in fish muscles tissue have been recorded for water bodies in this area (Table 3). The lowest values were established in *Oreochromis niloticus* from Ea Kao and Ea Súp reservoirs, while the highest values were found in *Bagarius* sp. in Lake Lak. Some specimens of *Oreochromis niloticus* and *Bagarius* sp. contained 0.01 and 4.1 μg Hg/g of tissue, respectively. It should be noted that both absolute and mean values established for the abovementioned species are edge values not only for Đắk Lak, but also for all the investigated water bodies of Central and South Vietnam.

Bình Thuận Province and Ba Ria-Vũng Tau Province. The mean values corresponded to levels of mercury concentration for the region (Table 3).

Can Tho City (Mekong River delta). There are two widespread closely related catfish species in waters of the river: *Clarias batrachus* and *C. macrocephalus*. Studies performed within a large amount of sampling (97 samples) showed the presence of interspecific differences in Hg content. Given the same weight and length in individuals, the mercury concentration in *C. macrocephalus* tissues was 2.5 times higher than that in the tissues of *C. batrachus* (Table 3).

DISCUSSION

Statistically significant dependences of Hg concentration in the muscle tissue of fish on its concentration in water or bottom sediments were not previously

Table 2. Mercury concentration in the muscle tissue of fish from water bodies of the Quang Nam province

Species	*n*	Weight, g	Length, cm	Hg, μg/g	R^2
			Tiên River		
Predators					
Channa gachua	9	31.3 ± 3.2 / 22–49	12 ± 0.6 / 10–15	0.27 ± 0.064 / 0.059–0.71	0.04
C. striata	13	84.1 ± 35.3 / 21–496	16 ± 1.7 / 11–34	0.24 ± 0.11 / 0.065–1.55	0.56
Monopterus albus	20	42.1 ± 2.1 / 31–72	36.3 ± 0.7 / 30–43	0.17 ± 0.02 / 0.069–0.41	0.12
Misgurnus sp.	20	14.6 ± 1.1 / 8–26	11.7 ± 0.3 / 9–14	0.19 ± 0.03 / 0.065–0.6	0.07
Omnivorous					
Anabas testudineus	6	12.8 ± 1.8 / 8–19	7.3 ± 0.4 / 6–9	0.12 ± 0.022 / 0.065–0.2	0.35
Clarias batrachus	1	87.8	21	0.012	–
C. macrocephalus	3	66.0 ± 18.1 / 48–102	16.0 ± 1.5 / 14–19	0.17 ± 0.014 / 0.15–0.2	–
			Tam Kỳ River		
Predators					
Channa striata	16	131.2 ± 24.7 / 27–441	23.8 ± 1.4 / 16–35	0.21 ± 0.026 / 0.09–0.44	0.32
Notopterus notopterus	18	37.4 ± 3.2 / 21–65	18.0 ± 0.5 / 16–22	0.15 ± 0.024 / 0.059–0.52	0.07
Omnivorous					
Anabas testudineus	21	27.3 ± 2.0 / 16–59	11.0 ± 0.3 / 9–15	0.15 ± 0.02 / 0.035–0.44	0.08
Clarias macrocephalus	3	62.7 ± 9.4 / 44–73	153 ± 0.4 / 14–17	0.19 ± 0.034 / 0.13–0.25	–
			Tranh River		
Herbivorous					
Oreochromis niloticus	8	55.8 ± 6.5 / 38–95	11.2 ± 0.4 / 10–13	0.11 ± 0.008 / 0.085–0.14	–0.37
Predators					
Bagarius yarelli	6	232.2 ± 30.4 / 167–328	31.0 ± 1.6 / 26–37	0.35 ± 0.024 / 0.29–0.44	0.24
Channa striata	4	47.3 ± 3.7 / 40–55	17.9 ± 0.5 / 17–19	0.3 ± 0.014 / 0.26–0.33	–
Mastacembelus armatus	10	39.3 ± 6.3 / 15–82	24.1 ± 1.5 / 18–32	0.43 ± 0.074 / 0.22–1.0	0.23
Monopterus albus	22	30.9 ± 1.5 / 20–49	33.4 ± 0.5 / 29–39	0.18 ± 0.033 / 0.021–0.7	–0.35
Mystus sp.	4	92.5 ± 40.2 / 20–205	21.1 ± 3.1 / 14–29	0.31 ± 0.06 / 0.2–0.47	–
Omnivorous					
Anabas testudineus	5	18.8 ± 2.4 / 14–27	12.2 ± 2.0 / 10–20	0.35 ± 0.041 / 0.25–0.46	–
Clarias batrachus	3	41.1 ± 3.7 / 35–48	14.5 ± 0.6 / 14–16	0.2 ± 0.04 / 0.13–0.26	–

Table 3. Mercury concentration in the muscle tissue of fish from water bodies of the Đak Lak, Binh Thuan, Bà Rịa – Vũng Tàu provinces and Can Tho city

Species	*n*	Weight, g	Length, cm	Hg, µg/g	R^2
			Đắk Lak Province (Lake Lak)		
Predators					
Bagarius sp.	10	160.1 ± 19.2 95–290	21.5 ± 0.6 19–25	2.55 ± 0.35 1.16–4.13	**0.71**
Channa striata	23	99.3 ± 11.1 54–204	18.7 ± 0.7 15–24	0.28 ± 0.028 0.088–0.61	0.45
Omnivorous					
Clarias fuscus	3	95.3 ± 30.8 63–157	18.3 ± 2.1 16–22	0.5 ± 0.3 0.19–1.1	–
			Ea Kao Reservoir		
Herbivorous					
Oreochromis niloticus	10	111.7 ± 10.9 64–174	13.3 ± 0.4 11–15	0.018 ± 0.002 0.012–0.027	–0.47
Predators					
Channa striata	10	110 ± 19.8 30–225	18.3 ± 1.3 12–24	0.14 ± 0.025 0.06–0.27	0.38
Omnivorous					
Anabas testudineus	10	13.2 ± 1.1 10–22	6.9 ± 0.2 6–8	0.07 ± 0.006 0.046–0.1	0.55
			Ea Súp Reservoir		
Herbivorous					
Oreochromis niloticus	10	276.5 ± 24.2 215–514	18.5 ± 0.4 16–22	0.035 ± 0.007 0.023–0.1	–0.19
Predators					
Channa striata	10	268.2 ± 4.8 249–291	25.8 ± 0.2 25–27	0.44 ± 0.024 0.32–0.55	0.07
			Bình Thuận Province (Hàm Luông District)		
Predators					
Channa striata	20	193.8 ± 28.1 70–472	22.7 ± 1.0 17–33	0.35 ± 0.05 0.12–0.87	0.06
Mystus sp.	15	13 ± 0.4 10–16	8.4 ± 0.1 8–9	0.31 ± 0.025 0.14–0.49	–0.29
Omnivorous					
Anabas testudineus	14	53.4 ± 4.4 37–93	11.3 ± 0.2 11–13	0.015 ± 0.002 0.009–0.03	–0.06
Clarias batrachus	1	146	20	0.037	–
			Bà Rịa-Vũng Tàu Province (Phuong Hai District)		
Predators					
Channa gachua	7	527.9 ± 57.8 384–788	33.1 ± 2.9 25–49	0.19 ± 0.011 0.16–0.24	**–0.63**

Table 3. (Contd.)

Species	*n*	Weight, g	Length, cm	Hg, μg/g	R^2
C. striata	6	94.1 ± 9.7 68–125	17.9 ± 0.5 16–20	0.097 ± 0.017 0.039–0.15	0.16
	Can Tho (Mekong River delta)				
Predators					
Channa striata	10	120.4 ± 11.6 58–194	20.9 ± 1.5 15–33	0.35 ± 0.044 0.07–0.57	**0.76**
Notopterus notopterus	18	64.1 ± 7.1 27–143	19.3 ± 4.6 13–24	0.17 ± 0.029 0.059–0.62	**0.71**
Omnivorous					
Clarias batrachus	47	128.5 ± 6.4 52–233	21.8 ± 0.4 17–28	0.1 ± 0.009 0.03–0.33	0.25
C. macrocephalus	50	131.5 ± 6.8 72–242	21.8 ± 0.4 17–21	0.26 ± 0.027 0.03–0.94	–0.04

identified in water bodies of the province of Khánh Hòa [1, 2]. This indirectly indicates that metal accumulates mainly in an alimentary (trophic) way [18]. Under natural conditions, this canal is the most effective and amounts to more than 90% of the total Hg entering the fish organism [10]. The intensity of absorption of different forms of Hg depends on the size of an individual, its diet, and its trophic position in the food chain [26]. The established high interspecific differences in metal content in the muscle tissue of fish in water bodies of Central and South Vietnam reflect their food differentiation. This dependence is most clearly observed in the classification of fish into ecological groups by food type [4]. Predators (*Channa gachua*, *C. striata*, *Ompok bimaculatus*, *Xenentodont cancila*, etc.) contain a greater amount of Hg than nonpredatory species (*Oreochromis niloticus, Mystacoleucus marginatus*, etc.) (Table 1–3), since predatory feeding contributes to more intensive metal accumulation [16, 35].

A comparative analysis of average Hg concentrations in muscles of fish in Cam Thuong, Suối Trầu, Ea Kao, and Ea Súp reservoirs showed that the metal content in individuals caught from "younger" water reservoirs is higher (Tables 2, 3). The construction of water reservoirs leads to a significant increase in metal concentration in fish even under background conditions of the presence of metal in river waters, rocks, and soils in flooding zones. The creation of artificial water bodies does not cause any general increase in Hg in the water medium; the increase in its amount in fish is due to the entry of metal from the upper layer of flooded soils and residues of vegetation cover [33]. An analysis of our own and available literature data [33] on the higher content of Hg in fish in the water reservoirs leads to the conclusion that this is a typical phenomenon for artificial water bodies of different climatic zones. As the water body grows old and its trophicity increases, the concentration of Hg decreases in fish.

A wide range of intraspecific fluctuations of Hg content was recorded for all the studied fish species in Vietnamese water bodies. It should be noted that the causes of these differences are described to a much lesser extent than intraspecific differences and, as a rule, are determined by a number of factors: age and size of individuals, physiological state, and migration processes [24]. The features of the ontogenetic fish development also play an important role, being determined by changes in the food spectrum and type at different life-cycle stages [8].

The length–weight dependence of Hg concentration in fish tissues is most often used in the analysis. However, the available data on tropical water bodies are ambiguous. The absence of correlation between Hg concentration and weight of fish has been recorded for *Cichla* sp. in the Rio Madeira River and lakes of the northern part of the Amazon basin [15]. A significant positive correlation between weight and mercury concentration in fish for *Cichla* sp. and *Hoplias malabaricus* (Bloch) from Tapajos and Rio Negro rivers (Brazil) has been described [11, 12]. At the same time, the same fish species are reported to have a negative correlation between the parameters under consideration [20]. In the research conducted by the authors, a significant correlation was established only for a small number of species. The nature of its trend is different in different water bodies (Tables 1–3); therefore, the intraspecific variability of metal content cannot be explained by ength–weight differences between fish, which is confirmed by data on Hg concentration in the

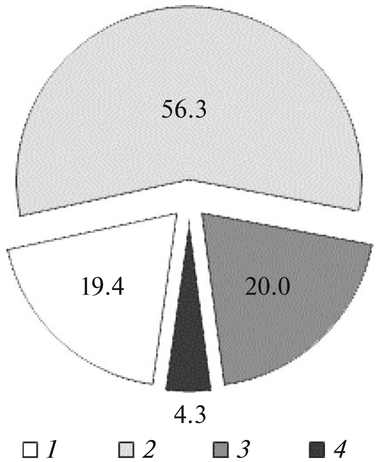

Fig. 2. Distribution of fish (%) with different mercury concentration in the muscle tissue (μg/g): (*1*) ≤0.1, (*2*) 0.1–0.5, (*3*) 0.51–1.5, and (*4*) ≥1.51.

muscle tissue of snakehead *Channa striata* in three selected weight groups in the Cái River, as well as by differences in metal content in this fish species in the upper and lower reaches of the river.

In the water bodies of both temperate and tropical latitudes, intraspecific ecological groups of individuals that differ in their adaptive set of morphological and behavioral features were revealed in fish dominant in number. These differences allow them to adapt to ecological subniches with different resources, utilize the food supply of habitats, and reduce inter- and intraspecific food competition in the most effective way [6, 30]. Probably, thin food differentiation is one of the factors determining the significant variation in Hg content in muscles of fish individuals of the same species.

The generalized data on the levels of Hg content in the muscle tissue of fish in the water bodies and watercourses in Central and South Vietnam are given in Fig. 2. The overwhelming majority of individuals (76% of the total sample volume) is characterized by concentrations that do not exceed the value of 0.5 μg Hg/g of dry weight (or 0.1 μg/g of wet weight), while higher values >1.5 μg/g of dry weight (or >0.3 μg/g of wet weight) were determined only in 4% (39 of 986 spec.). A comparison of Hg content in muscles of fish from different regions of the world where there are no local sources of pollution and the entry of metal is largely due to atmospheric deposition is given in Table 4. Despite many factors contributing to the formation of spatial, temporal, and interspecific variability, the concentration of metal in the fish of the investigated water bodies is significantly lower than that in freshwater ecosystems of temperate latitudes in North America, Europe, Russia, and tropical South America. It should be noted that similar features are observed in water bodies of tropical Africa, where even lower values have been recorded [9]. An analysis of causes determining this phenomenon is of undoubted scientific interest. These differences cannot be due to the difference in the amount of metal entering water bodies of different climatic zones. There is no evidence that the atmospheric deposition of Hg in the tropical part of Southeast Asia is lower than that in most of regions of the world. On the contrary, all models of the global balance of Hg consider the Asia region the basic "donor" of its anthropogenic emission [28]. At the same time, differences in a number of other physicochemical and biological parameters of ecosystems that influence methylation/demethylation and bioaccumulation of Hg could possibly serve as a partial explanation to low concentrations of metal in fish in tropical Asia and Africa compared with water bodies of temperate latitudes in North America and Europe.

Table 4. Mercury concentration (μg/g of dry weight) in the muscle tissue of fish from different regions of the world

Region	Species	
	non predatory	predators
Africa*	0.1	0.3
Vietnam**	0.15	0.5
South America (Brazil)*	0.5	3
North America*:		
United States	0.5	3
Canada	0.3	2.5
Russia*	0.35	2
Scandinavia*	0.4	4.3

* According to works [9, 12, 25, 27].
** Authors' data.

On the one hand, methylation of Hg in water systems is a key step in the transformation of its migration properties and in the involvement of metal into the trophic transfer. There is a general concept that this process is largely a microbiologically mediated, intracellular, enzymatic reaction [29]. The bioavailability of inorganic Hg forms is determined by the content of neutral dissolved complexes; their concentration can serve as a limiting link [32]. The photochemical reduction of Hg^{2+} is an important mechanism for generating Hg^0 in a wide range of water bodies. Due to a high volatility, elementary Hg is quickly emitted from the water column [22]. Methylmercury already formed in the medium is subject to photodecomposition [19]. Therefore, the high solar insolation in tropics may contribute to the active processes of photolysis of different metal forms and compounds. Volatilization of Hg^0 from the water surface plays an important role in the global cycle of Hg and may be one of the factors limiting its availability for methylating microorganisms [23].

On the other hand, unlike the large diversity of species inhabiting terrestrial ecosystems, the biota of rivers and lakes in tropics (except for fish) is usually not considered more complicated than that in water bodies of the temperate zone [7]. The tropical rivers and lakes are distinguished by the rare occurrence of large zooplankton species that are widespread in water bodies of temperate latitudes; even if they are present in any tropical rivers and lakes, they can be found only in small numbers and with much smaller size. Many water bodies of the tropical region are rich in endemic fish species and are characterized by a very high species diversity of ichthyofauna [14]. The relative number of fish species with pronounced food selectiveness tends to increase in the direction from high latitudes to low latitudes as a result of higher competition for food resources [4], which is confirmed by data on the content of Hg in two closely related catfish species from the Mekong River delta (*Clarias batrachus* and *C. marcocephalus*). It is believed that they occupy similar ecological niches in *C. batrachus* (Table 3). The high branching of food chains of trophic ecosystems may also contribute to an effective dispersion of metal in them. On the whole, living organisms in trophic regions show a more rapid growth. Under the conditions of rapidly growing population, the rates of growth of organisms can exceed the rate of metal absorption, which leads to a decrease in the amount of accumulated Hg [31]. By contrast, opposite changes are observed in water bodies of temperate and northern latitudes, where higher levels of mercury content have been recorded in the muscle tissue of fish. The structure of communities and the organization of the trophic web are simplified, the size characteristics and the degree of domination increase, and the fish species diversity decreases (up to 1–2 species) [5, 17].

A number of works [8, 12, 20, 27] show data on the high content of Hg in fish in the water bodies of the Amazon River basin (South America). First, research in these water areas has a longer history and is associated with anthropogenic human activity on Au and Ag mining, which results in an intensive emission of Hg into the environment. According to approximate estimates, this resource causes more than 55% of all metal emissions in the region under consideration, which leads to the active contamination of air, soil, water, bottom sediments, and biota [27]. Second, the water bodies where high Hg values have been recorded in fish tissues are characterized by specific hydrochemical conditions. For instance, the Rio Negro River (Amazon River basin) has a high water-color index and low pH values (4–5) [8]. These two factors can have a significant influence on the most intensive accumulation of Hg in biota [25, 32]; therefore, according to the authors, the data on South American water bodies should be correctly used in assessing the regional levels of Hg content and interpreting the features of biogeochemical processes of metal migration in tropical ecosystems.

CONCLUSIONS

It was established that Central and South Vietnam is characterized by lower levels of Hg content in the muscle tissue of fish than water bodies of temperate and northern latitudes in North America, Europe, Russia, and tropical regions of South America (which are not subject to local anthropogenic contamination). A wide range of intraspecific differences in metal content are typical of all the studied species.

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