Трансформация экосистем
Ecosystem Transformation

ISSN 2619-0931 Online
www.ecosysttrans.com

DOI: https://doi.org/10.23859/estr-251129
EDN: https://elibrary.ru/wlfmsj
UDC 574.43+592

Article

Mercury content in the invertebrates of lower trophic levels of aquatic and terrestrial ecosystems of the southern coast of Sakhalin Island, Far East, Russia

Yu.G. Udodenko[1, 2*], T.B. Kamshilova[1], T.A. Devyatova[3], I.I. Gordeev[4, 5, 6]

[1] *I.D. Papanin Institute for Biology of Inland Waters, Russian Academy of Sciences, Borok 109, Nekouz District, Yaroslavl Oblast, 152742 Russia*

[2] *Cherepovets State University, Prospekt Lunacharskogo St. 5, Cherepovets, Vologda Oblast, 162602 Russia*

[3] *Voronezh State University, Universitetskaya Square 1, Voronezh, 394018 Russia*

[4] *Lomonosov Moscow State University, Leninskie Gory 1, Moscow, 119234 Russia*

[5] *Russian Federal Research Institute of Fisheries and Oceanography, Okruzhnoy proezd 19, Moscow, 105187 Russia*

[6] *Sakhalin State University, Kommunistichesky Prospekt St. 33, Yuzhno-Sakhalinsk, 693000 Russia*

**udu@mail.ru*

Abstract. Mercury concentrations were determined in invertebrates of various taxonomic groups and trophic levels sampled in August 2025 near Cape Anastasia, Crillon Peninsula, Sakhalin Island (Far East, Russia). Terrestrial and freshwater invertebrates contained significantly more mercury than those inhabiting the marine intertidal zone. The highest mercury concentrations were registered for the earthworm, *Octolasion lacteum* (650 ± 387 ng/g), and the lowest – for isopod crustaceans of the genus *Idotea* (28 ± 9 ng/g). The food spectra and trophic group (type of feeding) affect significantly the variability of mercury concentrations in regard to taxonomic and ecological groups of invertebrates inhabiting the same biotope. The mercury concentrations obtained for studied invertebrates can be used as background values.

Keywords: earthworms, spiders, harvestmen, mayflies, crustaceans, food webs, river, sea, littoral zone

Funding. The work was supported by the Non-Commercial Charitable Foundation "Support of Biological Research "BIOM" (project no. 14/2025). The analytical work was carried out under State Assignment no. 24032500015-7 for the I.D. Papanin Institute of Biology of Inland Waters of the Russian Academy of Sciences.

ORCID:
Yu.G. Udodenko, https://orcid.org/0000-0003-0789-4847
T.B. Kamshilova, https://orcid.org/0000-0002-8535-9658
I.I. Gordeev, https://orcid.org/0000-0002-6650-9120

To cite this article: Udodenko, Yu.G. et al., 2026. Mercury content in the invertebrates of lower trophic levels of aquatic and terrestrial ecosystems of the southern coast of Sakhalin Island, Far East, Russia. *Ecosystem Transformation* **9** (3), 130–144. https://doi.org/10.23859/estr-251129

Received: 29.11.2025
Accepted: 28.02.2026
Published online: 29.08.2026

DOI: https://doi.org/10.23859/estr-251129
EDN: https://elibrary.ru/wlfmsj
УДК 574.43+592

Научная статья

Ртуть в беспозвоночных нижних трофических уровней водных и наземных экосистем южного побережья о. Сахалин

Ю.Г. Удоденко[1, 2*], Т.Б. Камшилова[1], Т.А. Девятова[3], И.И. Гордеев[4, 5, 6]

[1] *Институт биологии внутренних вод им. И.Д. Папанина РАН, 152742, Россия, Ярославская обл., Некоузский район, пос. Борок, д. 109*

[2] *Череповецкий государственный университет, 162602, Россия, Вологодская обл., г. Череповец, пр-кт Луначарского, д. 5*

[3] *Воронежский государственный университет, 394018, Россия, г. Воронеж, Университетская площадь, д. 1*

[4] *Московский государственный университет им. М.В. Ломоносова, 119234, Россия, г. Москва, Ленинские горы, д. 1*

[5] *Всероссийский научно-исследовательский институт рыбного хозяйства и океанографии, 105187, Россия, г. Москва, Окружной пр-д, д. 19*

[6] *Сахалинский государственный университет, 693000, Россия, г. Южно-Сахалинск, Коммунистический пр-кт, д. 33*

**udu@mail.ru*

Аннотация. Определена концентрация ртути в беспозвоночных различных таксономических групп и трофических гильдий, отобранных в августе 2025 г в окрестностях мыса Анастасии, п-ов Крильон, о. Сахалин. Наземные и пресноводные беспозвоночные содержали статистически значимо больше ртути по сравнению с беспозвоночными, обитающими на морской литорали. Наибольшие концентрации отмечены у дождевых червей вида *Octolasion lacteum* – 650 ± 387 нг/г, наименьшие у равноногих раков рода *Idotea* – 28 ± 9 нг/г. Показано, что тип и способ питания животных значительно влияют на вариабельность концентраций ртути между таксономическими и экологическими группами беспозвоночных, обитающих в одном биотопе на южном побережье о. Сахалин. Выявленные концентрации ртути в организме беспозвоночных могут быть использованы как фоновые значения в дальнейших исследованиях.

Ключевые слова: дождевые черви, пауки, сенокосцы, поденки, ракообразные, пищевые сети, река, море, литораль

Финансирование. Работа была поддержана Некоммерческим благотворительным фондом "Поддержка биологических исследований БИОМ" (проект № 14/2025). Аналитические работы выполнены в рамках государственного задания 24032500015-7 Института биологии внутренних вод им. И.Д. Папанина РАН.

ORCID:
Ю.Г. Удоденко, https://orcid.org/0000-0003-0789-4847
Т.Б. Камшилова, https://orcid.org/0000-0002-8535-9658
И.И. Гордеев, https://orcid.org/0000-0002-6650-9120

Для цитирования: Удоденко, Ю.Г. и др., 2026. Ртуть в беспозвоночных нижних трофических уровней водных и наземных экосистем южного побережья о. Сахалин. *Трансформация экосистем* **9** (3), 130–144. https://doi.org/10.23859/estr-251129

Поступила в редакцию: 29.11.2025
Принята к печати: 28.02.2026
Опубликована онлайн: 29.08.2026

Introduction

The relationship between the chemical composition of animal organisms and the environment is undeniable. However, depending on the biogeochemical conditions of the biotope, the levels of accumulation of various compounds in tissues and organs can vary significantly, even at similar background concentrations.

Mercury emissions into the atmosphere from natural and anthropogenic sources are the starting point for the migration of this element in the environment (Driscoll et al., 2013; Selin, 2009). According to existing estimates, approximately 5000–6000 tons of mercury enter the atmosphere annually, of which 1/3 to 2/3 are of anthropogenic origin (UN Environment Programme, 2019). With air masses, atomic mercury (Hg^0) is transported over long distances; after its oxidation to the divalent ion (Hg^{2+}), it is deposited on the land and water surface at a significant distance from the source. In aquatic ecosystems and wetlands, under the influence of microorganisms, part of the divalent mercury is converted into extremely toxic methylmercury (CH_3Hg^+), which readily enters food webs (Scheuhammer et al., 2012).

Food is the main source of methylmercury for animals (Chételat et al., 2020). Organic mercury compounds accumulate more rapidly in biota than inorganic compounds; they are also excreted more slowly, leading to more efficient bioaccumulation of mercury through the food chain. The highest mercury concentrations are typically found in the organs and tissues of species occupying the upper trophic levels in terrestrial and aquatic ecosystems (Rumbold et al., 2018; Seco et al., 2021). Methylmercury accumulated in the body poses a health threat to most vertebrates, including humans (Scheuhammer et al., 2015).

Mercury levels in an ecosystem are often assessed through its concentrations in the tissues of upper-trophic-level vertebrates (Chételat et al., 2020; Eagles-Smith et al., 2016). At the same time, studies that assess mercury's role in the food web by measuring its concentrations in organisms at lower trophic levels remain limited and fragmented (Martins et al., 2021).

Invertebrate species typically occupy narrow ecological niches and exhibit conservative feeding habits. Most do not undertake long-distance migrations and instead persist under relatively stable biogeochemical conditions. Since invertebrates constitute a key food resource for many vertebrates, their mercury content can help predict contaminant levels in upper-trophic-level consumers. Consequently, the most abundant invertebrate species, which spanning diverse taxa and ecological groups within a biotope, serve as reliable indicators of an ecosystem's biogeochemical status.

Particular attention should be given to identifying the most informative indicator for assessing the ecological status of remote areas with minimal anthropogenic pressure. The results of exploratory studies are essential for informed geographic zoning and rational land use. The southern coast of Sakhalin Island is particularly interesting from this perspective (Gordeev et al., 2024).

The study aims to compare mercury accumulation levels in the most common terrestrial, freshwater, and marine invertebrates occupying lower trophic levels in food webs off the southern coast of Sakhalin Island.

Materials and methods

The material was collected on August 4–14, 2025, in the vicinity of Cape Anastasia, Crillon Peninsula, Sakhalin Island (Fig. 1). Three main sampling sites were set within the study area: (1) the Marine Station "Aniva"; (2) the lower reaches of the Anastasia River; and (3) the marine littoral zone (up to 150-m wide).

At each main sampling site, the most abundantly represented macroinvertebrates of different taxa and trophic groups were sampled (Table 1). At the Anastasia River and on the marine littoral zone, material was collected at several sample plots (SPs), presumably differing from each other in biogeochemical conditions. The SPs on the flat section of the Anastasia River were located at distances of 300 and 2500 m from the river mouth. In the marine littoral zone, two SPs were surveyed: (1) the area 100 m to the north of the Marine Station "Aniva", covered with the thickets of surfgrass, *Phyllospadix iwatensis* Makino 1931, with neighboring "bird colony" (rare rocky outcrops 200 m from the shore, occupied by a colony of pelagic cormorants *Urile pelagicus* Pallas, 1811); and (2) a gravel area without macrophytes adjacent to the Marine Station. Terrestrial and aquatic invertebrates were collected using standard methods (Byzova et al., 1987; Rukovodstvo..., 1992). Spiders and harvestmen were collected by hand; earthworms, by manual soil sampling; aquatic invertebrates – with a net. All invertebrates were preserved in 95% ethanol and stored prior to analysis.

Mercury content was determined by pyrolysis using an RA-915M atomic absorption spectrometer (Lumex, Russia) equipped with a PIRO pyrolytic attachment. This method is widely used in the analysis of mercury content in various biological materials (Fernandes et al., 2024; Panichev and Panicheva, 2015; Sholupov et al., 2004).

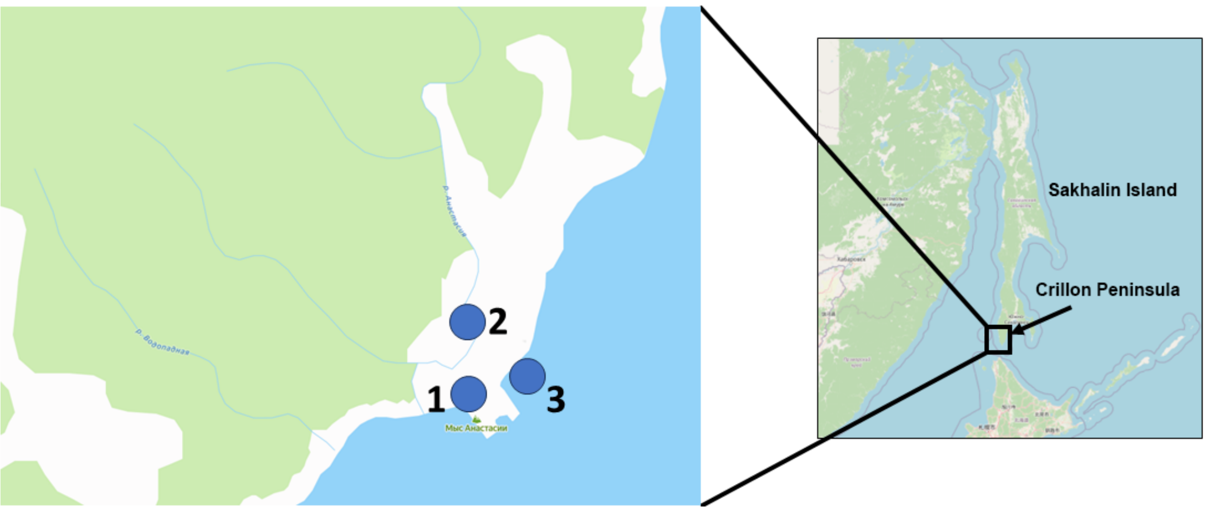

Fig. 1. Schematic map of the study area and sampling sites (see Table 1 for explanations).

Table 1. Location and brief description of the surveyed areas

Station number	Coordinates N	Coordinates E	Brief description	Collected material
1	46.017007	142.170037	Marine Station "Aniva	Earthworms, orb-weaver spiders, harvestmen
2	46.017719	142.166797	Anastasia River	Larvae of mayflies (family Heptageniidae); freshwater amphipods (family Gammaridae)
3	46.017829	142.172485	The littoral zone northwards the Biological Station "Aniva" and the bird colony	Marine crustaceans (*Idotea* sp., *Pagurus* sp., Mysidae)
	46.01508	142.171411	Littoral zone near the Marine Station "Aniva"	

Before analysis, all samples were dried in a drying oven at 40 °C for 48 hours to remove residual moisture. Depending on the volume of material, each sample was analyzed one to three times. For small invertebrates with a dry weight of less than 5 mg (amphipods, mayfly larvae, harvestmen), mercury concentrations were determined in a single sample containing 3–4 individuals. Measurement accuracy was monitored using DORM-4 international standards; error did not exceed 5–7%.

Mercury concentrations are presented per unit of dry weight as mean ± standard deviation ($m \pm SD$). Nonparametric methods were applied for statistical analysis of the obtained results. The Mann-Whitney *U*-test was used to assess the differences between two independent samples. Differences between three or more independent samples were assessed using the Kruskal-Wallis *H*-test.

Results

Mercury content in terrestrial invertebrates

The highest average mercury concentrations were observed in earthworm *Octolasion lacteum* (Örley, 1885) (Fig. 2). In another species of earthworm, *Lumbricus rubellus* (Hoffmeister, 1843), the average mercury content was 6.5 times lower, a statistically significant difference. For this species, no statistically significant differences in mercury content were found between mature and juvenile individuals ($Z = 0.28$; $p = 0.777$). No juveniles were found for *O. lacteum*.

Lower mercury concentrations are observed in arachnids, which are part of grazing food webs. Mercury concentrations in orb-weaving spiders (Araneidae) and harvestmen (Opiliones) were comparable and did not differ significantly (Fig. 3).

Mercury content in aquatic invertebrates

Among freshwater invertebrates, the highest mercury concentrations were found in the amphipods belonging to the family Gammaridae (Fig. 4). Mayfly larvae (family Heptageniidae) were characterized by half the mercury content of amphipods. However, no statistically significant differences were found between amphipods and Heptageniidae larvae from different collection sites.

Among the marine invertebrates studied, the highest mercury concentrations were found in mysids. Meanwhile, isopods of the genus *Idotea* and hermit crabs of the genus *Pagurus* contained 2.5–3.0 times less mercury than mysids (Fig. 5). These differences were statistically significant.

The mercury content in the isopods of the genus *Idotea* collected near the bird colony was statistically significantly lower than in representatives of the same genus inhabiting the coastal littoral zone ($H = 15.6$, $p = 0.013$).

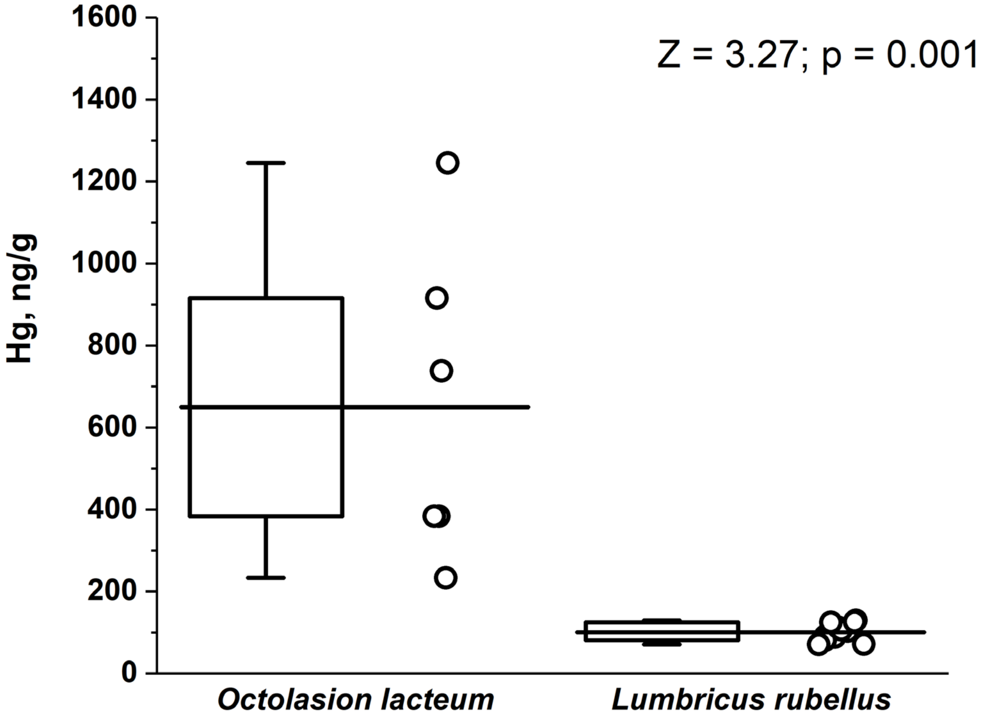

Fig. 2. Mercury content in the bodies of the studied earthworm species. Here and further on: the solid line inside the "box" is the average value; the circles are individual measurements.

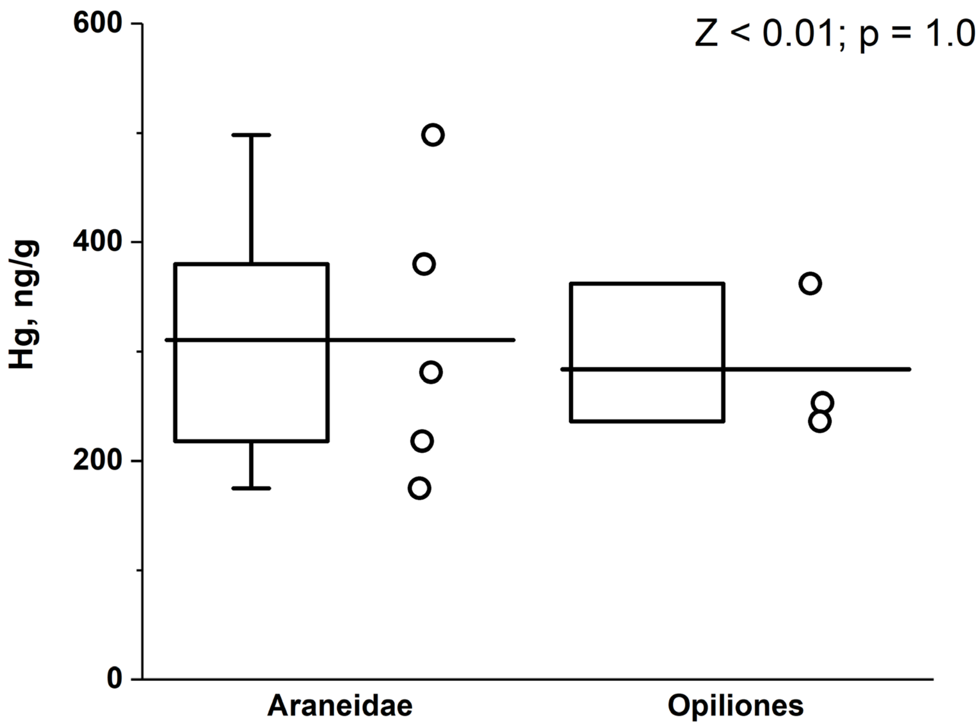

Fig. 3. Mercury content in the bodies of the studied arachnid species.

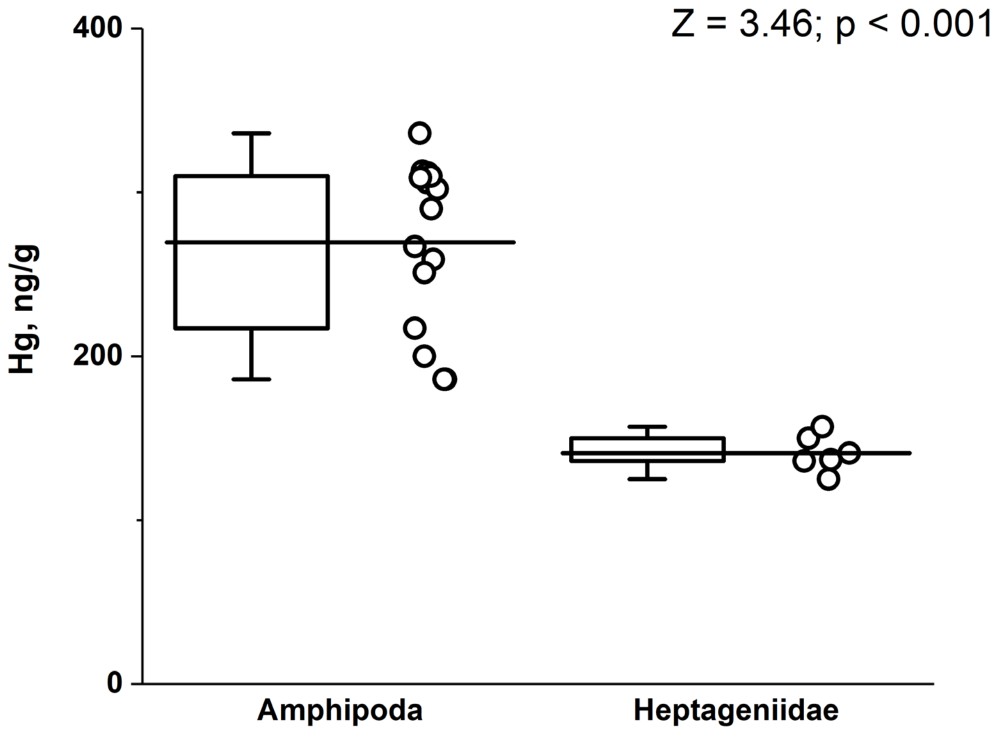

Fig. 4. Mercury content in freshwater invertebrates sampled in the Anastasia River.

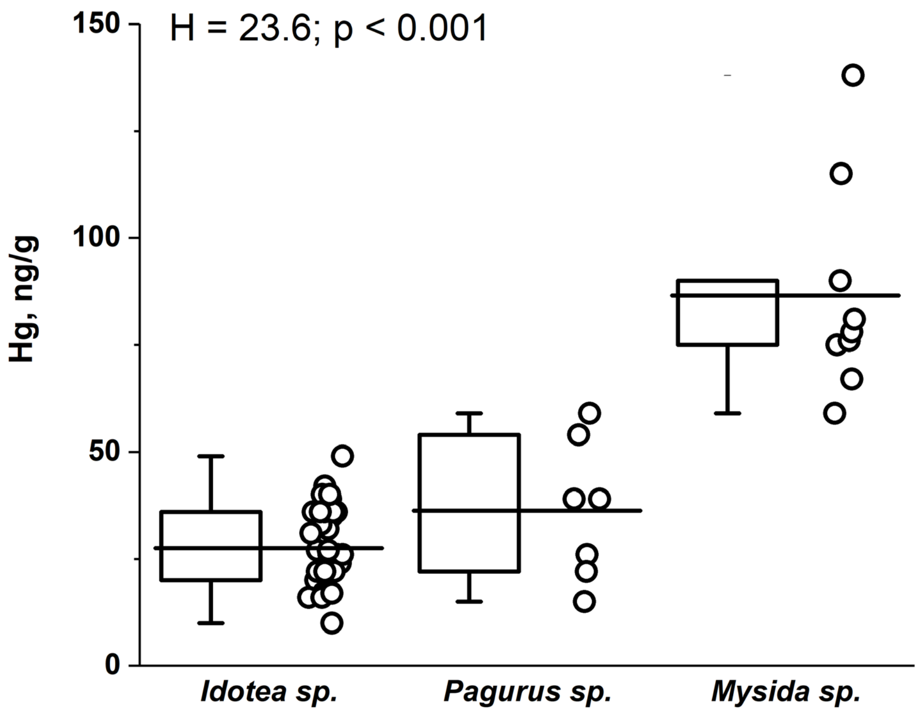

Fig. 5. Mercury content in crustaceans sampled in the marine littoral zone.

Discussion

The patterns of mercury accumulation in different ecological groups of terrestrial and aquatic invertebrates remain poorly understood. However, mercury distribution among animals inhabiting the same biotope follows a pattern typical for vertebrates: predatory species have higher mercury levels than those feeding on plant matter and detritus (Komov et al., 2017a; Razavi et al., 2020; Sinclair et al., 2024). Earthworms are the only exception, as they accumulate mercury at concentrations several times higher than other invertebrate species (Komov et al., 2017b; Udodenko et al., 2012; Zhang et al., 2009).

The mercury content in *O. lacteum*, inhabiting the soils of the study area, exceeds that of all other studied groups of terrestrial and aquatic invertebrates of the southern coast of Sakhalin. Average mercury concentrations in this species are comparable to the values recorded in earthworms from moist soils of the forest park zone of Cherepovets and the Voronezh Nature Reserve (Udodenko et al., 2012, 2022a). Despite the fact that a large metallurgical plant is located in Cherepovets, which can be a source of various heavy metals in the environment, no elevated mercury concentrations were found in the bodies of invertebrates living within the urban biotopes. At the same time, the average mercury concentration in *O. lacteum* was 1.5–3.0 times lower than in the earthworms of the genus *Allolobophora* and *Drawida* from Liaoning Province, China (Zhang et al., 2009), and *Octolasion cyaneum* from the forest ecosystems of Switzerland (Rieder et al., 2011). On the contrary, mercury content in *Lumbricus rubellus* from the southern coast of Sakhalin is half that of representatives of the same species from forest ecosystems in Switzerland and is comparable to that obtained for the worms of the genus *Limnodrilus* from Liaoning Province.

According to the studies performed in Switzerland, earthworm species belonging to various morpho-ecological groups differ significantly in mercury content (Ernst and Frey, 2007; Rieder et al., 2011). The mercury concentration in soil-litter species (including *Lumbricus rubellus)* was statistically significantly lower than that in true soil species, which include *O. lacteum.* The results of our study are consistent with data obtained for Switzerland. The differences in mercury concentrations found between the two earthworm species from the southern coast of Sakhalin Island suggest that mercury levels in the food resources of these species also differ accordingly.

According to earlier studies, the mercury concentrations in harvestmen were significantly lower than in spiders inhabiting the same biotope (Rimmer et al., 2010; Udodenko et al., 2022a). We assume that such differences are associated with the dietary patterns characteristic of representatives of different arachnid orders. Spiders are obligate predators and hunt primarily insects from various taxonomic groups. Unlike spiders, harvestmen's diet includes plant remains and detritus, although some of their representatives are predatory. In the present study, harvestmen were not identified down to the species level, and the available literature lacks information on the diet of Far Eastern species (Gongal'skii et al., 2014; Marusik, 2005). We suggest that harvestmen from the southern coast of Sakhalin are predators or have a mixed diet; as a result, they accumulate mercury in quantities comparable to those of spiders.

Mercury concentrations in amphipods from the study area exceeded those reported for conspecifics or related taxa in known mercury-contaminated ecosystems. For instance, amphipods collected from the Anastasia River contained 1.5–2.0 times more mercury than those inhabiting an industrial emissions zone in the St. Lawrence River Valley (Canada) (Hodson et al., 2014). In contrast, mayfly larvae from the Anastasia River exhibited lower mercury levels compared to those from rivers affected by anthropogenic mercury pollution. As an example, mayflies from the Boroo River (Selenge Province, northern Mongolia), where a mid-20th-century industrial accident introduced large quantities of metallic mercury into the ecosystem, showed mercury concentrations 10–15 times higher than those measured in mayflies from the southern coast of Sakhalin (Udodenko et al., 2022b).

Studies comparing mercury levels across different taxa and trophic groups of aquatic invertebrates remain scarce and have yielded inconsistent results. For example, crustaceans were found to contain higher mercury concentrations than mayfly larvae in western Oregon, USA (Jackson et al., 2020), whereas no significant difference was observed between Heptageniidae mayflies and Gammaridae amphipods in tributary streams of the Finger Lakes, New York State (Razavi et al., 2020). In the Anastasia River, differences in mercury concentrations between amphipods and mayfly larvae are likely attributable to their distinct feeding strategies. Heptageniidae larvae are phytophagous scrapers that graze on periphytic algae attached to rocks, thus participating in a grazing-based food web. In contrast, Gammaridae amphipods are detritivorous shredders that consume dead organic matter (often of terrestrial origin) and operate within a detrital food web. The elevated mercury levels in amphipods suggest that mercury transfer in this river is primarily channeled through the detrital pathway. Furthermore, the lack of spatial variation in mercury concentrations between amphipods and mayfly larvae across sampling sites indicates relatively homogeneous biogeochemical conditions in the studied lower reaches of the Anastasia River. These findings underscore that dietary habits critically influence mercury uptake, ultimately driving interspecific differences in tissue concentrations among freshwater invertebrates.

It should be noted that mercury concentrations in marine intertidal invertebrates along the southern coast of Sakhalin island were 5–10 times lower than those measured in freshwater and terrestrial invertebrates from the same region. Similar low levels have been reported for marine intertidal invertebrates across diverse taxonomic groups in coastal areas of Poland and Spitsbergen remote from anthropogenic mercury sources (Jędruch et al., 2018; Korejwo et al., 2022). These observations suggest that marine macrozoobenthos generally exhibits lower mercury burdens compared to terrestrial invertebrates, which is a pattern likely rooted in fundamental differences in mercury geochemical cycling between terrestrial and marine systems. In coastal zones, dissolved organic matter and clay-silt particles that bind Hg^{2+} are transported into the littoral zone via lateral runoff, but they do not accumulate there; instead, they are flushed offshore during ebb tides (Bareket et al., 2016). Consequently, mercury availability in shallow intertidal habitats remains limited. This dynamic raises the possibility that invertebrates inhabiting deeper waters of the Sea of Okhotsk may contain substantially higher mercury concentrations than their intertidal counterparts (Liu et al., 2020; Sisma-Ventura et al., 2024). A similar pattern (lower mercury levels in aquatic versus adjacent terrestrial invertebrates) has also been documented in mountainous coastal ecosystems along California (Rundio et al., 2022), reinforcing the role of ecosystem type in shaping mercury bioaccumulation.

Therefore, the feeding type and foraging strategy of animals drive differences in mercury concentrations among taxonomic and ecological groups of invertebrates co-occurring within the same biotope on the southern coast of Sakhalin. At the same time, local biogeochemical conditions, governing the availability of bioaccessible mercury forms at the base of food webs, appear to be the primary determinant of mercury levels in biota within individual biotopes.

To date, regulatory thresholds for mercury concentrations in tissues, above which physiological impairments occur, have not been established for most animal species. Only a limited number of studies have identified such thresholds, primarily in Arctic birds and marine mammals (Dietz et al., 2013). The absence of standardized toxicity benchmarks complicates direct evaluation of the potential adverse effects of the mercury levels detected in Sakhalin's invertebrates. Nevertheless, comparison with data from other regions remote from anthropogenic mercury sources indicates that mercury concentrations in invertebrates along the southern coast of Sakhalin Island fall within natural background ranges. This suggests that current levels are unlikely to pose a risk either to the invertebrates themselves or to higher trophic-level consumers.

Conclusions

In the south of Sakhalin Island, terrestrial and riverine environments are more favorable for mercury uptake into food webs than coastal marine biotopes. This is evidenced by higher mercury concentrations in terrestrial and freshwater invertebrates at lower trophic levels compared to invertebrates in the marine intertidal zone.

Mercury levels in the studied species fall within the range typical for biota inhabiting biotopes with minimal mercury loads. The studied invertebrates may play a significant role in mercury transport through terrestrial and aquatic food webs along the southern coast of Sakhalin. However, the obtained mercury concentrations do not appear to pose a health risk to animals or humans, and the ecological and toxicological status of the southern coast of Sakhalin Island should be characterized as satisfactory.

The obtained mercury concentrations in biota can be considered as reference values for the study area. The results of future studies on the biogeochemical behavior of mercury in various ecosystem components within Sakhalin should be compared with the data obtained in this study.

References

Bareket, M.M., Bookman, R., Katsman, R., De Stigter, H., Herut, B., 2016. The role of transport processes of particulate mercury in modifying marine anthropogenic secondary sources, the case of Haifa bay, Israel. *Marine Pollution Bulletin* **105** (1), 286–291. https://doi.org/10.1016/j.marpolbul.2016.02.014

Byzova, Yu.B., Gilyarov, M.S., Dunger, V., Zakharov, A.A., Kozlovskaya, L.S. et al., 1987. Kolichestvennye metody v pochvennoy zoologii [Quantitative methods in soil zoology]. Nauka, Moscow, USSR, 288 p. (In Russian).

Chételat, J., Ackerman, J.T., Eagles-Smith, C.A., Hebert, C.E., 2020. Methylmercury exposure in wildlife: A review of the ecological and physiological processes affecting contaminant concentrations and their interpretation. *Science of The Total Environment* **711**, 135117. https://doi.org/10.1016/j.scitotenv.2019.135117

Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T., *et al.*, 2013. What are the toxicological effects of mercury in Arctic biota? *Science of The Total Environment* **443**, 775–790. https://doi.org/10.1016/j.scitotenv.2012.11.046

Driscoll, C.T., Mason, R.P., Chan, H.M., Jacob, D.J., Pirrone, N., 2013. Mercury as a global pollutant: Sources, pathways and effects. *Environmental Science & Technology* **47**, 4967–4983. https://doi.org/10.1021/es305071v

Eagles-Smith, C.A., Wiener, J.G., Eckley, C.S., Willacker, J.J., Evers, D.C. et al., 2016. Mercury in western North America: A synthesis of environmental contamination, fluxes, bioaccumulation, and risk to fish and wildlife. *Science of The Total Environment* **568**, 1213–1226. https://doi.org/10.1016/j.scitotenv.2016.05.094

Ernst, G., Frey, B., 2007. The effect of feeding behavior on Hg accumulation in the ecophysiologically different earthworms *Lumbricus terrestris* and *Octolaseon cyaneum*: A microcosm experiment. *Soil Biology and Biochemistry* **39** (1), 386–390. https://doi.org/10.1016/j.soilbio.2006.07.020

Fernandes, I.O., Monteiro, L.C., De Miranda, V.L., Rodrigues, Y.O.S., De Freitas Muniz, D.H. et al., 2024. Mercury distribution in organisms, litter, and soils of the Middle Araguaia floodplain in Brazil. *Environmental Science and Pollution Research* **31** (14), 20925–20940. https://doi.org/10.1007/s11356-024-32317-x

Gongal'skii, K.B., Kuznetsova, D.M., Elagin, A.D., Maliavin, S.A., Zaitsev, A.S., 2014. Pochvennaia mezofauna iuga ostrova Kunashir (Kuril'skie ostrova) [Soil mesofauna of the south of Kunashir Island (Kuril Islands).]. *Doklady Rossiiskoi akademii nauk [Reports of the Russian Academy of Sciences]* **457** (3), 1–4. (In Russian).

Gordeev, I.I., Tokarev, Iu.S., Davydov, E.A., Ekimova, I.A., Drozdov, K.A. et al., 2024. Kompleksnaia nauchno-issledovatel'skaia ekspeditsiia «Kril'on 2023»: pervye nakhodki i predvaritel'nye rezul'taty [Complex research expedition "Crillon 2023": first findings and preliminary results.]. *Vestnik moskovskogo universiteta. Seriia 16. Biologiia [Moscow University Bulletin. Series 16. Biology]* **79** (1), 28–49. (In Russian). https://doi.org/10.55959/MSU0137-0952-16-79-1-4

Hodson, P.V., Norris, K., Berquist, M., Campbell, L.M., Ridal, J.J., 2014. Mercury concentrations in amphipods and fish of the Saint Lawrence River (Canada) are unrelated to concentrations of legacy mercury in sediments. *Science of The Total Environment* **494–495**, 218–228. https://doi.org/10.1016/j.scitotenv.2014.06.137

Jackson, A.K., Eagles-Smith, C.A., Emery, C., 2020. Spatial variation in aquatic invertebrate and riparian songbird mercury exposure across a river-reservoir system with a legacy of mercury contamination. *Ecotoxicology* **29** (8), 1195–1204. https://doi.org/10.1007/s10646-019-02043-z

Jędruch, A., Bełdowska, M., Graca, B., 2018. Seasonal variation in accumulation of mercury in the benthic macrofauna in a temperate coastal zone (Gulf of Gdańsk). *Ecotoxicology and Environmental Safety* **164**, 305–316. https://doi.org/10.1016/j.ecoenv.2018.08.040

Komov, V.T., Ivanova, E.S., Poddubnaya, N.Y., Gremyachikh, V.A., 2017a. Mercury in soil, earthworms and organs of voles *Myodes glareolus* and shrew *Sorex araneus* in the vicinity of an industrial complex in Northwest Russia (Cherepovets). *Environmental Monitoring and Assessment* **189** (3), 104. https://doi.org/10.1007/s10661-017-5799-4

Komov, V.T., Gremyachikh, V.A., Udodenko, Yu.G., Shchedrova, E.V., Elizarov, M.Yu., 2017b. Rtut' v abioticheskikh i bioticheskikh komponentakh vodnykh i nazemnykh ekosistem poselka gorodskogo tipa na beregu Rybinskogo vodokhranilishcha [Mercury in abiotic and biotic components of aquatic and terrestrial ecosystems in the urban settlement on the shore of the Rybinsk reservoir]. *Trudy instituta biologii vnutrennikh vod im. I.D. Papanina RAN [Transactions of Papanin Institute for Biology of Inland Waters RAS]* **77** (80), 34–56. (In Russian). https://doi.org/10.24411/0320-3557-2017-10003

Korejwo, E., Saniewska, D., Bełdowski, J., Balazy, P., Saniewski, M., 2022. Mercury concentration and speciation in benthic organisms from Isfjorden, Svalbard. *Marine Pollution Bulletin* **184**, 114115. https://doi.org/10.1016/j.marpolbul.2022.114115

Liu, M., Xiao, W., Zhang, Q., Shi, L., Wang, X., Xu, Y., 2020. Methylmercury bioaccumulation in deepest ocean fauna: Implications for ocean mercury biotransport through food webs. *Environmental Science & Technology Letters* **7** (7), 469–476. https://doi.org/10.1021/acs.estlett.0c00299

Martins, B.M., O'Driscoll, N.J., Mallory, M.L., Canário, J., 2021. A review of freshwater invertebrates as biomonitors of methylmercury: the importance of more complete physical and chemical reporting. *Bulletin of Environmental Contamination and Toxicology* **107** (5), 801–808. https://doi.org/10.1007/s00128-021-03274-9

Marusik, Yu.M., 2005. Paukoobraznye (Arachnida: Aranei, Opiliones) severnogo Okhotomor'ya [Arachnids (Arachnida: Aranei, Opiliones) of Northern Cisokhotia]. *Evraziyskiy entomologicheskiy zhurnal [Eurasian Entomological Journal]* **4** (3), 187–208. (In Russian).

Panichev, N.A., Panicheva, S.E., 2015. Determination of total mercury in fish and sea products by direct thermal decomposition atomic absorption spectrometry. *Food Chemistry* **166**, 432–441. https://doi.org/10.1016/j.foodchem.2014.06.032

Razavi, N.R., Halfman, J.D., Cushman, S.F., Massey, T., Beutner, R. et al., 2020. Mercury concentrations in fish and invertebrates of the Finger Lakes in central New York, USA. *Ecotoxicology* **29** (10), 1673–1685. https://doi.org/10.1007/s10646-019-02132-z

Rieder, S.R., Brunner, I., Horvat, M., Jacobs, A., Frey, B., 2011. Accumulation of mercury and methylmercury by mushrooms and earthworms from forest soils. *Environmental Pollution* **159** (10), 2861–2869. https://doi.org/10.1016/j.envpol.2011.04.040

Rimmer, C.C., Miller, E.K., McFarland, K.P., Taylor, R.J., Faccio, S.D., 2010. Mercury bioaccumulation and trophic transfer in the terrestrial food web of a montane forest. *Ecotoxicology* **19** (4), 697–709. https://doi.org/10.1007/s10646-009-0443-x\

Rukovodstvo po gidrobiologicheskomu monitoringu presnovodnykh ekosistem [Guidelines for hydrobiological monitoring of freshwater ecosystems], 1992. Gidrometeoizdat, Saint-Petersburg, Russia, 318 p. (In Russian).

Rumbold, D.G., Lange, T.R., Richard, D., DelPizzo, G., Hass, N., 2018. Mercury biomagnification through food webs along a salinity gradient down-estuary from a biological hotspot. *Estuarine, Coastal and Shelf Science* **200**, 116–125. https://doi.org/10.1016/j.ecss.2017.10.018

Rundio, D.E., Rivera, R., Weiss-Penzias, P.S., 2022. High mercury concentrations in steelhead/rainbow trout, sculpin, and terrestrial invertebrates in a stream-riparian food web in coastal California. *Ecotoxicology* **31** (10), 1506–1519. https://doi.org/10.1007/s10646-022-02608-5

Scheuhammer, A.M., Basu, N., Evers, D.C., Heinz, G.H., Sandheinrich, M.B., Bank, M.S., 2012. Ecotoxicology of mercury in fish and wildlife: Recent advances. In: Bank, M. (ed.), *Mercury in the Environment*. University of California Press, Los Angeles, USA, 223–238. https://doi.org/10.1525/california/9780520271630.003.0011

Scheuhammer, A., Braune, B., Chan, H.M., Frouin, H., Krey, A. et al., 2015. Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic. *Science of The Total Environment* **509–510**, 91–103. https://doi.org/10.1016/j.scitotenv.2014.05.142

Seco, J., Aparício, S., Brierley, A.S., Bustamante, P., Ceia, F.R. et al., 2021. Mercury biomagnification in a Southern Ocean food web. *Environmental Pollution* **275**, 116620. https://doi.org/10.1016/j.envpol.2021.116620

Selin, N.E., 2009. Global biogeochemical cycling of mercury: A review. *Annual Review of Environment and Resources* **34** (1), 43–63. https://doi.org/10.1146/annurev.environ.051308.084314

Sholupov, S., Pogarev, S., Ryzhov, V., Mashyanov, N., Stroganov, A., 2004. Zeeman atomic absorption spectrometer RA-915+ for direct determination of mercury in air and complex matrix samples. *Fuel Processing Technology* **85** (6–7), 473–485. https://doi.org/10.1016/j.fuproc.2003.11.003

Sinclair, C.A., Garcia, T.S., Eagles-Smith, C.A., 2024. A meta-analysis of mercury biomagnification in freshwater predatory invertebrates: Community diversity and dietary exposure drive variability. *Environmental Science & Technology* **58** (43), 19429–19439. https://doi.org/10.1021/acs.est.4c05920

Sisma-Ventura, G., Silverman, J., Guy-Haim, T., Stern, N., Shachnai, A. et al., 2024. Accumulation of total mercury in deep-sea sediments and biota across a bathymetric gradient in the Southeastern Mediterranean Sea. *Chemosphere* **351**, 141201. https://doi.org/10.1016/j.chemosphere.2024.141201

Udodenko, Yu.G., Devyatova, T.A., Komov, V.T., Tregubov, O.V., Odintsov, A.N., 2012. Soderzhanie rtuti v pochvakh i zemlyanykh chervyakh (Oligochaeta, Lumbricidae) Voronezhskogo zapovednika [Mercury content in soils and earthworms (Oligochaeta, Lumbricidae) Voronezh Nature Reserve]. *Vestnik Voronezhskogo gosudarstvennogo universiteta. Seriya: Khimiya. Biologiya. Farmatsiya [Bulletin of Voronezh State University. Series: Chemistry, Biology, Pharmacy*] **2**, 209–215. (In Russian).

Udodenko, Yu.G., Ivanova, E.S., Komov, V.T., Bazhenova, D.E., Belik, A.V., 2022a. Soderzhanie rtuti v pochvennykh bespozvonochnykh rekreatsionnoy zony krupnogo promyshlennogo goroda (g. Cherepovets) [Mercury content in soil invertebrates of the recreational zone of a large industrial city (Cherepovets)]. *Trudy instituta biologii vnutrennikh vod im. I.D. Papanina RAN [Transactions of Papanin Institute for Biology of Inland Waters RAS]* **100** (103), 54–64. (In Russian). https://doi.org/10.47021/0320-3557-2022-57-64

Udodenko, Y.G., Robinson, C.T., Choijil, J., Badrakh, R., Munkhbat, J. et al., 2022b. Mercury levels in sediment, fish and macroinvertebrates of the Boroo River, northern Mongolia, under the legacy of gold mining. *Ecotoxicology* **31** (2), 312–323. https://doi.org/10.1007/s10646-021-02502-6

UN Environment Programme, 2019. Global Mercury Assessment 2018. Chemicals and Health Branch Geneva. Narayana Press, Geneva, Switzerland, 58 p.

Zhang, Z.S., Zheng, D.M., Wang, Q.C., Lv, X.G., 2009. Bioaccumulation of total and methyl mercury in three earthworm species (*Drawida* sp., *Allolobophora* sp., and *Limnodrilus* sp.). *Bulletin of Environmental Contamination and Toxicology* **83** (6), 937–942. https://doi.org/10.1007/s00128-009-9872-8

Список литературы

Бызова, Ю.Б., Гиляров, М.С., Дунгер, В., Захаров, А.А., Козловская, Л.С. и др., 1987. Количественные методы в почвенной зоологии. Наука, Москва, СССР, 288 с.

Гонгальский, К.Б., Кузнецова, Д.М., Елагин, А.Д., Малявин, С.А., Зайцев, А.С., 2014. Почвенная мезофауна юга острова Кунашир (Курильские острова). *Доклады Российской академии наук* **457** (3), 1–4.

Гордеев, И.И., Токарев, Ю.С., Давыдов, Е.А., Екимова, И.А., Дроздов, К.А. и др., 2024. Комплексная научно-исследовательская экспедиция «Крильон 2023»: первые находки и предварительные результаты. *Вестник московского университета. Серия 16. Биология* **79** (1), 28–49. https://doi.org/10.55959/MSU0137-0952-16-79-1-4

Марусик, Ю.М., 2005. Паукообразные (Arachnida: Aranei, Opiliones) северного Охотоморья. *Евразиатский энтомологический журнал* **4** (3), 187–208.

Комов, В.Т., Гремячих, В.А., Удоденко, Ю.Г., Щедрова, Е.В., Елизаров, М.Ю., 2017. Ртуть в абиотических и биотических компонентах водных и наземных экосистем поселка городского типа на берегу Рыбинского водохранилища, *Труды института биологии внутренних вод им. И.Д. Папанина РАН* **77** (80), 34–56. https://doi.org/10.24411/0320-3557-2017-10003

Руководство по гидробиологическому мониторингу пресноводных экосистем, 1992. Абакумов, В.А. (ред.). Гидрометеоиздат, Санкт-Петербург, Россия, 318 с.

Удоденко, Ю.Г., Девятова, Т.А., Комов, В.Т., Трегубов, О.В., Одинцов, А.Н., 2012. Содержание ртути в почвах и земляных червях (Oligochaeta, Lumbricidae) Воронежского заповедника. *Вестник Воронежского государственного университета. Серия: Химия. Биология. Фармация* **2**, 209–215.

Удоденко, Ю.Г., Иванова, Е.С., Комов, В.Т., Баженова, Д.Э., Белик, А.В., 2022. Содержание ртути в почвенных беспозвоночных рекреационной зоны крупного промышленного города (г. Череповец). *Труды института биологии внутренних вод им. И.Д. Папанина РАН* **100** (103), 54–64. https://doi.org/10.47021/0320-3557-2022-57-64

Bareket, M.M., Bookman, R., Katsman, R., De Stigter, H., Herut, B., 2016. The role of transport processes of particulate mercury in modifying marine anthropogenic secondary sources, the case of Haifa bay, Israel. *Marine Pollution Bulletin* **105** (1), 286–291. https://doi.org/10.1016/j.marpolbul.2016.02.014

Chételat, J., Ackerman, J.T., Eagles-Smith, C.A., Hebert, C.E., 2020. Methylmercury exposure in wildlife: A review of the ecological and physiological processes affecting contaminant concentrations and their interpretation. *Science of The Total Environment* **711**, 135117. https://doi.org/10.1016/j.scitotenv.2019.135117

Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T., *et al.*, 2013. What are the toxicological effects of mercury in Arctic biota? *Science of The Total Environment* **443**, 775–790. https://doi.org/10.1016/j.scitotenv.2012.11.046

Driscoll, C.T., Mason, R.P., Chan, H.M., Jacob, D.J., Pirrone, N., 2013. Mercury as a global pollutant: Sources, pathways and effects. *Environmental Science & Technology* **47**, 4967–4983. https://doi.org/10.1021/es305071v

Eagles-Smith, C.A., Wiener, J.G., Eckley, C.S., Willacker, J.J., Evers, D.C. et al., 2016. Mercury in western North America: A synthesis of environmental contamination, fluxes, bioaccumulation, and risk to fish and wildlife. *Science of The Total Environment* **568**, 1213–1226. https://doi.org/10.1016/j.scitotenv.2016.05.094

Ernst, G., Frey, B., 2007. The effect of feeding behavior on Hg accumulation in the ecophysiologically different earthworms *Lumbricus terrestris* and *Octolaseon cyaneum*: A microcosm experiment. *Soil Biology and Biochemistry* **39** (1), 386–390. https://doi.org/10.1016/j.soilbio.2006.07.020

Fernandes, I.O., Monteiro, L.C., De Miranda, V.L., Rodrigues, Y.O.S., De Freitas Muniz, D.H. et al., 2024. Mercury distribution in organisms, litter, and soils of the Middle Araguaia floodplain in Brazil. *Environmental Science and Pollution Research* **31** (14), 20925–20940. https://doi.org/10.1007/s11356-024-32317-x

Hodson, P.V., Norris, K., Berquist, M., Campbell, L.M., Ridal, J.J., 2014. Mercury concentrations in amphipods and fish of the Saint Lawrence River (Canada) are unrelated to concentrations of legacy mercury in sediments. *Science of The Total Environment* **494–495**, 218–228. https://doi.org/10.1016/j.scitotenv.2014.06.137

Jackson, A.K., Eagles-Smith, C.A., Emery, C., 2020. Spatial variation in aquatic invertebrate and riparian songbird mercury exposure across a river-reservoir system with a legacy of mercury contamination. *Ecotoxicology* **29** (8), 1195–1204. https://doi.org/10.1007/s10646-019-02043-z

Jędruch, A., Bełdowska, M., Graca, B., 2018. Seasonal variation in accumulation of mercury in the benthic macrofauna in a temperate coastal zone (Gulf of Gdańsk). *Ecotoxicology and Environmental Safety* **164**, 305–316. https://doi.org/10.1016/j.ecoenv.2018.08.040

Komov, V.T., Ivanova, E.S., Poddubnaya, N.Y., Gremyachikh, V.A., 2017. Mercury in soil, earthworms and organs of voles *Myodes glareolus* and shrew *Sorex araneus* in the vicinity of an industrial complex in Northwest Russia (Cherepovets). *Environmental Monitoring and Assessment* **189** (3), 104. https://doi.org/10.1007/s10661-017-5799-4

Korejwo, E., Saniewska, D., Bełdowski, J., Balazy, P., Saniewski, M., 2022. Mercury concentration and speciation in benthic organisms from Isfjorden, Svalbard. *Marine Pollution Bulletin* **184**, 114115. https://doi.org/10.1016/j.marpolbul.2022.114115

Liu, M., Xiao, W., Zhang, Q., Shi, L., Wang, X., Xu, Y., 2020. Methylmercury bioaccumulation in deepest ocean fauna: Implications for ocean mercury biotransport through food webs. *Environmental Science & Technology Letters* **7** (7), 469–476. https://doi.org/10.1021/acs.estlett.0c00299

Martins, B.M., O'Driscoll, N.J., Mallory, M.L., Canário, J., 2021. A review of freshwater invertebrates as biomonitors of methylmercury: the importance of more complete physical and chemical reporting. *Bulletin of Environmental Contamination and Toxicology* **107** (5), 801–808. https://doi.org/10.1007/s00128-021-03274-9

Panichev, N.A., Panicheva, S.E., 2015. Determination of total mercury in fish and sea products by direct thermal decomposition atomic absorption spectrometry. *Food Chemistry* **166**, 432–441. https://doi.org/10.1016/j.foodchem.2014.06.032

Razavi, N.R., Halfman, J.D., Cushman, S.F., Massey, T., Beutner, R. et al., 2020. Mercury concentrations in fish and invertebrates of the Finger Lakes in central New York, USA. *Ecotoxicology* **29** (10), 1673–1685. https://doi.org/10.1007/s10646-019-02132-z

Rieder, S.R., Brunner, I., Horvat, M., Jacobs, A., Frey, B., 2011. Accumulation of mercury and methylmercury by mushrooms and earthworms from forest soils. *Environmental Pollution* **159** (10), 2861–2869. https://doi.org/10.1016/j.envpol.2011.04.040

Rimmer, C.C., Miller, E.K., McFarland, K.P., Taylor, R.J., Faccio, S.D., 2010. Mercury bioaccumulation and trophic transfer in the terrestrial food web of a montane forest. *Ecotoxicology* **19** (4), 697–709. https://doi.org/10.1007/s10646-009-0443-x

Rumbold, D.G., Lange, T.R., Richard, D., DelPizzo, G., Hass, N., 2018. Mercury biomagnification through food webs along a salinity gradient down-estuary from a biological hotspot. *Estuarine, Coastal and Shelf Science* **200**, 116–125. https://doi.org/10.1016/j.ecss.2017.10.018

Rundio, D.E., Rivera, R., Weiss-Penzias, P.S., 2022. High mercury concentrations in steelhead/rainbow trout, sculpin, and terrestrial invertebrates in a stream-riparian food web in coastal California. *Ecotoxicology* **31** (10), 1506–1519. https://doi.org/10.1007/s10646-022-02608-5

Scheuhammer, A.M., Basu, N., Evers, D.C., Heinz, G.H., Sandheinrich, M.B., Bank, M.S., 2012. Ecotoxicology of mercury in fish and wildlife: Recent advances. In: Bank, M. (ed.), *Mercury in the Environment*. University of California Press, Los Angeles, USA, 223–238. https://doi.org/10.1525/california/9780520271630.003.0011

Scheuhammer, A., Braune, B., Chan, H.M., Frouin, H., Krey, A. et al., 2015. Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic. *Science of The Total Environment* **509–510**, 91–103. https://doi.org/10.1016/j.scitotenv.2014.05.142

Seco, J., Aparício, S., Brierley, A.S., Bustamante, P., Ceia, F.R. et al., 2021. Mercury biomagnification in a Southern Ocean food web. *Environmental Pollution* **275**, 116620. https://doi.org/10.1016/j.envpol.2021.116620

Selin, N.E., 2009. Global biogeochemical cycling of mercury: A review. *Annual Review of Environment and Resources* **34** (1), 43–63. https://doi.org/10.1146/annurev.environ.051308.084314

Sholupov, S., Pogarev, S., Ryzhov, V., Mashyanov, N., Stroganov, A., 2004. Zeeman atomic absorption spectrometer RA-915+ for direct determination of mercury in air and complex matrix samples. *Fuel Processing Technology* **85** (6–7), 473–485. https://doi.org/10.1016/j.fuproc.2003.11.003

Sinclair, C.A., Garcia, T.S., Eagles-Smith, C.A., 2024. A meta-analysis of mercury biomagnification in freshwater predatory invertebrates: Community diversity and dietary exposure drive variability. *Environmental Science & Technology* **58** (43), 19429–19439. https://doi.org/10.1021/acs.est.4c05920

Sisma-Ventura, G., Silverman, J., Guy-Haim, T., Stern, N., Shachnai, A. et al., 2024. Accumulation of total mercury in deep-sea sediments and biota across a bathymetric gradient in the Southeastern Mediterranean Sea. *Chemosphere* **351**, 141201. https://doi.org/10.1016/j.chemosphere.2024.141201

Udodenko, Y.G., Robinson, C.T., Choijil, J., Badrakh, R., Munkhbat, J. et al., 2022. Mercury levels in sediment, fish and macroinvertebrates of the Boroo River, northern Mongolia, under the legacy of gold mining. *Ecotoxicology* **31** (2), 312–323. https://doi.org/10.1007/s10646-021-02502-6

UN Environment Programme, 2019. Global Mercury Assessment 2018. Chemicals and Health Branch Geneva. Narayana Press, Geneva, Switzerland, 58 p.

Zhang, Z.S., Zheng, D.M., Wang, Q.C., Lv, X.G., 2009. Bioaccumulation of total and methyl mercury in three earthworm species (*Drawida* sp., *Allolobophora* sp., and *Limnodrilus* sp.). *Bulletin of Environmental Contamination and Toxicology* **83** (6), 937–942. https://doi.org/10.1007/s00128-009-9872-8