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Original Paper

Total mercury content in soils and lake sediments of Vilkitsky Island (Kara Sea)

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Mercury threatens Arctic ecosystems due to its well known deleterious effects. The development of energy resources in the Russian Arctic is currently being planned, which will inevitably be accompanied by emissions of heavy metals into the environment, but little is known about the distribution of mercury in soils of the permafrost regions. Total mercury (THg) concentrations were investigated in soils and lake sediments of Vilkitsky Island located in remote area of the Arctic. The concentration of mercury in soils varied from 1 to 36,6 ng/g, in lake sediments – from 2.0 to 5.8 ng/g. In sandy soils of the iseland the concentration of THg was minimal and was usually not higher than10 ng/g, whereas in loamy soils it was 3.5 times higher. Correlation analysis has shown that THg concentration depended primarily on particle size distribution, in a lesser degree – on total carbon and total nitrogen concentrations. The soils of Viltisky Island have one of the lowest mercury concentration in comparison to soils of other Arctic territories, because of the predominance of sandy marine sediments and low soil organic matter content. Under influence of human activities, THg content has increased three-fold on average. The highest concentrations were observed in soils of an abandoned polar station. Calculation of CF and Igeo coefficients demonstrated the high level of mercury pollution on local sites. The maximum content of mercury (25.7–36.7 ng/g) was observed in coastal sediments. It is assumed that the increased mercury content is a consequence of translocation. Thus, the coastal areas of the Arctic islands are at the greatest danger of pollution.

Keywords: mercury pollution, soil texture, soil organic matter, Arenosols, Arctic

1 Introduction

Mercury, a highly toxic pollutant, represents a global threat because of its long-distance travel and toxicity. In gaseous form mercury is transported over long distances and reaches remote areas of Arctic and Antarctic (Bargagli et al., 2007; Poissant et al., 2008). Currently, human activities have caused a considerable increase in Hg concentration in the Arctic environment compared to pre-industrial times (Riget et al., 2011). As a result, the soils of the Arctic are belived to be an important global absorber of atmospheric mercury (Olson et al., 2018). Yet little is known about the distribution and variation of mercury in soils of the permafrost region (Sun et al., 2017).

Mercury pollution in the Arctic causes substantial concern, especially after the discovery of the phenomenon of mercury depletion in the atmosphere of polar regions (AMDES) (Poissant et al., 2008). The AMDES phenomenon is most strongly manifested on the sea coasts, where sea salts in the air act as crystallization nuclei and stimulate the deposition of pollutants (Garbarino et al., 2002). Therefore, the study of mercury pollution of the coastal areas is of a particular interest.

Recent discoveries suggest that the mercury cycle in the Arctic is complex and involves transformation processes, perhaps unique to polar climates, which lead to enhanced Hg deposition and transformation to bioavailable forms (AMAP 2005). The growing mercury pollution in the Arctic and Subarcticis and its increasing bioavailability are considered to be a significant threat to the health of northern populations and vegetation (Hammerschmidt et al., 2006). Hg concentrations in contemporary

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indigenous peoples are higher than ever before, the same trend is emerging for some studied animal species (AMAP, 2005). Moreover, the tundra is a place where domestic deer graze. The North of Western Siberia is currently one of the main centers of reindeer husbandry in the world, more than 670 thousand reindeer graze here (Zuev, 2015). Throughout the year, deer are on pasture maintenance and need plant resources. A significant growth of livestock number, as well as the disturbance of vegetation under human influence, led to a reduction in the area of pastures, and in some areas to desertification of territories (Kryazhimsky, 2011). Considering a shortage of pasture area, the assessment of food quality becomes especially relevant, one of the criteria of which is its safe chemical composition.

The study of mercury in the Russian Arctic is also of great importance since industrial development is planned here in the near future. The industrial development of the Arctic is accompanied by the deposition of various heavy metals, including mercury (AMAP, 2005). Nonetheless, there are only few studies of mercury content in the soils of the Russian Arctic. Only recently has mercury content been studied in the soils of the Yamal Peninsula (Ji et al., 2019), Bely Island (Moskovchenko et al., 2017), and data on Hg content in lake sediments appeared (Tatsii and Baranov, 2022). Upcoming industrial development makes it necessary to assess the background Hg content in soils.

This paper presents the study of the total mercury (THg) content in the soils and lake sediments of Vilkitsky Island located in the Kara Sea, the Russian sector of the Arctic Ocean. Currently, there is no human activity on the island, which makes it possible to consider it a reference when assessing the mercury content in uncontaminated soils. Concurrently, the presence of sites where anthropogenic objects used to be located makes it possible to determine the human influence on the intake of mercury into ecosystems. The objectives of the study were as follows:

1. to identify the background concentrations of mercury;
2. to determine the effect of soil texture, pH and the amount of organic matter on the THg content;
3. to assess the level of anthropogenic pollution.

2 Material and methods

2.1 Study area

Vilkitsky Island is located in the South-East of the Kara Sea, north of the Gydan Peninsula between 73° 22′ and 73° 32′ N, and 75° 21′ to 76° 06′ E (Figure 1). The island is a flat plain with a height of less than 6 m above sea level with numerous thermokarst lakes. The region belongs to a marine Arctic cold climate, with low air temperature and precipitation. According to the nearest weather station Dixon, the average annual air temperature on the iseland is -10 °C, the average air temperature of the warmest month (August) is +6.0 °C, the avearge annual precipitation is 360 mm. Permafrost and cryogenic landforms are widespread everywhere. The short duration of the summer season determines the shallow depth of seasonal thawing (not exceeding 0.8–1.0 m even in the sands).

The island is composed of holocene marine sediments (Kolesnikov et al., 2017). Due to low temperatures, the vegetation cover is sparse. Sedge-moss and lichen communities of high arctic tundras are common on the watershed, sedge-sphagnum communities are developed on terraces along the lake shores.

The studied soils were formed on Pleistocene and Holocene marine sediments. The soil cover on the watersheds is dominated by Arenosols, which are formed on sandy sediments. In the relief depressions the gleyization occur due to high moisture content and the occurrence of permafrost close to the surface. The vertical structure of the soil cover is influenced by cryogenic processes (cryogenic heaving, solifluction), which deforms the boundaries of soil horizons.

The north-east part of the island was affected by the highest degree of anthropogenic impact. The abandoned residential area and a polar station are located on this part of the island. Around the place, as well as on the shore of the Kara Sea, there are unauthorized landfills of solid household and industrial waste, piles of scrap metal. The island is currently uninhabited (Kolesnikov et al., 2017). There is no industrial activity in the direct surroundings of the island. The existing gas fields are located approximately 250 km to the South-West on the Yamal Peninsula. Norilsk metallurgical enterprises, which are a source of nickel and copper pollution, are located 600 km to the South-East.

2.2 Sampling

Field work was carried out in August 2019. When placing the sampling points, the task was to cover the dominant soil types in various landscape positions. Soil samples were taken at 38 sites located in different parts of the island.

When investigating the geochemical properties of polar soils, depending on the objectives, several sampling methods are used. To assess the spatial variation of soil chemistry at each sampling site, one sample is usually taken from a surface layer of different thickness, from 3 to 25 cm (Moskovchenko et al., 2017; Gulińska et al., 2003). To determine the distribution of chenical elements

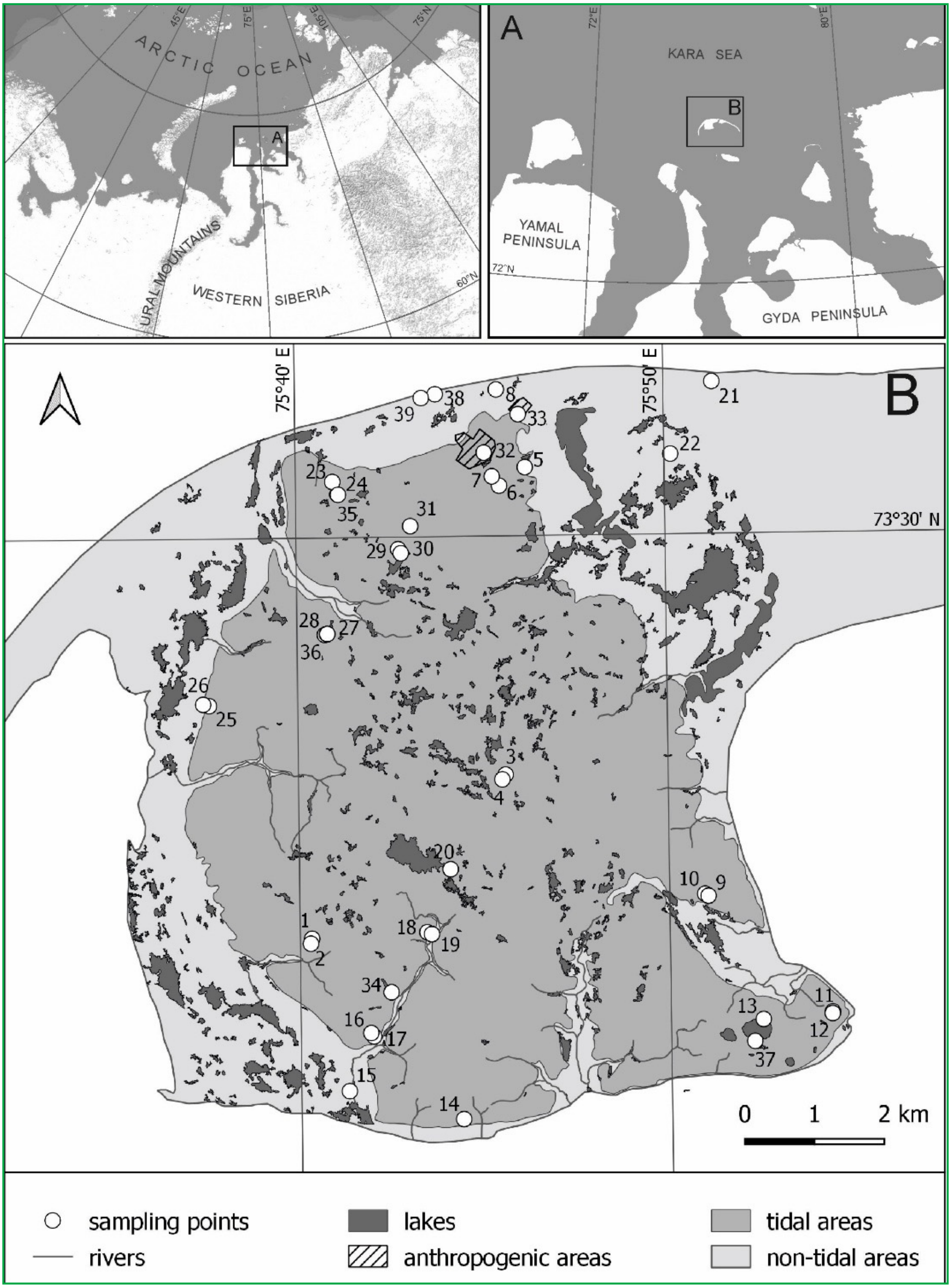

Figure 1 Geographical position of Vilkitsky Island and soil sampling sites

along the profile, sampling from each genetic horizon is carried out (Ji et al., 2019) or sampling is limited to one sample taken at a fixed depth without reference to soil horizons (Abakumov et al., 2017; Halbach et al., 2017). The applied methodology aimed at determining intra-soil translocation of elements. The samples were taken from the top 5 cm of soil (top soil) under the organic debris and from the middle part of the profile, i.e. from 15–20 cm depth (deeper soil) (Halbach et al., 2017). A similar methodology with subdivision of soil horizons into surface organogenic and middle soil horizons was used to estimate the background concentrations of elements in the soils of northern Western Siberia (Opekunova et al., 2019). The sampling from the 15–20 cm layer was reasoned by the following considerations:

1. this layer was thawed in all sites during the sampling period;
2. it is in this layer that plant roots are located.

At some sites soils thawed dipper and then soil samples were also taken from a depth of 35–40 cm.

The sampling was accompanied by a description of the soil profile morphology. The study of anthropogenic sources of mercury was carried out at three sites: on the territory of an abandoned residential area, on the territory of an abandoned polar station, and on the coastal area, where ships were unloaded, including the unloading of coal for heating purposes. The sampling sites are shown in Figure 1 (no. 8, 31 and 32). The full description of the sampling sites is presented in Table 1.

2.3 Methods of chemical analysis

Analytical studies were conducted in the laboratories of Tyumen State University: Research Resource Center "Natural Resource Management and Physico-Chemical Research, and International Integrated Research Laboratory for Climate Change, Land Use and Biodiversity of the Institute of Environmental and Agricultural Biology (X-BIO)".

The soil particle size distribution was determined by PARIO particle size analyzer (METER Group, München, Germany). Soil pH was measured in water extraction at a soil:solution ratio 1 : 2.5 with ST3100 pH meter (Ohaus, USA), electrical conductivity was measured in the same water extract as pH with HI 2003-02 edge (Hanna, USA). Total carbon (TC) and total nitrogen (TN) content measurements were performed using a vario TOC (Elementar) device.

To analyze the THg content, 20 to 100 mg of a sample were used. The samples were placed in a dispenser spoon, injected into a prefix heated to 700 °C, where the catalytic degradation of the compounds of the soil sample matrix and the release of mercury occured. Mercury vapor entered the analytical cell of the analyzer and was detected. The analytical signal was processed using RAPID software. All soil samples were analyzed in two replicates by atomic absorption spectrometry with RA-915M and pyrolytic prefix RP-91S (Lumex, Russia). The calibration coefficient was determined based on a standard soil sample of sod-podzolic sandy loam (SDPS-3). Stability control of the calibration coefficient was carried out before the measurements.

2.4 Statistical processing of the results

Statistical data processing was performed using Statistica 10.0 software.The normality of the distribution was controled using the Kolmogorov-Smirnov test. Correlation coefficients were calculated to determine the relationship between the mercury content and physico-chemical parameters, the amount of organic matter, soil texture. Since the test showed that the content of mercury in the soils did not correspond to the normal distribution, Spearman's rank correlation coefficients were calculated at the significance level ($P < 0.05$) to identify the relationship between the content of THg and pH, TC, TN, the clay and silt content.

The mercury pool in the soil was calculated using the formula:

$$MP = Ci \times BD \times h$$

where: MP – the mercury pool, mg/m^2; Ci – the mercury concentration, ng/g;, BD – the soil bulk density, kg/dm^3; h – the depth of the soil layer (m)

For calculations, data on the average density of soils in Western Siberia were used (Syso, 2007): sandy soils – 1.6 kg/dm^3, loam soils – 1.2 kg/dm^3, surface organic horizons – 0.50 kg/dm^3, peat – 0.1 kg/dm^3. The calculation was carried out for the soil layer of 0.2 m, since this layer is thawed in summer time in different soil types.

To assess the level of pollution, the values of the contamination factor CF and the Igeo coefficient were calculated according to Hakanson's (1980) and Muller's classifications (1981) (Table 2) using the following formulas:

$$CF = Cn/Cb$$

$$Igeo = \ln Cn/1.5 \times Cb$$

where: Cn – the concentration of Hg in the soil; Cb – the background concentration, 1.5 is a constant that allows to analyze natural fluctuations in the content of this substance in the environment

Table 1 Description of sampling sites

Sample number	Latitude, longitude	Soil type	Undisturbed/disturbed soils	Sampling date
1	73° 26′ 54.6″ N, 75° 40′ 19.2″ E	arenosols protic	undisturbed	13. 7. 2019
2	73° 26′ 52.4″ N, 75° 40′ 15.6″ E	arenosols gleyic	undisturbed	13. 7. 2019
3	73° 28′ 09.5″ N, 75° 45′ 36.1″ E	arenosols protic	undisturbed	13. 7. 2019
4	73° 28′ 07.3″ N, 75° 45′ 30.8″ E	arenosols gleyic	undisturbed	13. 7. 2019
5	73° 30′ 31.7″ N, 75° 46′ 13.6″ E	fluviosols gleyic	undisturbed	14. 7. 2019
6	73° 30′ 23.3″ N, 75° 45′ 31.3″ E	arenosols gleyic	undisturbed	14. 7. 2019
7	73° 30′ 27.6″ N 75° 45′ 19.7″ E	arenosols protic	undisturbed	14. 7. 2019
8	73° 31′ 07.8″ N, 75° 45′ 28.2″ E	sands	disturbed	15. 7. 2019
9	73° 27′ 13.2″ N, 75° 50′ 57.2″ E	arenosols protic	undisturbed	16. 7. 2019
10	73° 27′ 12.3″ N, 75° 51′ 02.8″ E	arenosols gleyic	undisturbed	16. 7. 2019
11	73° 26′ 17.9″ N, 75° 54′ 21.6″ E	arenosols gleyic	undisturbed	16. 7. 2019
12	73° 26′ 17.1″ N, 75° 54′ 21.3″ E	arenosols gleyic	undisturbed	16. 7. 2019
13	73° 26′ 14.9″ N, 75° 52′ 29.2″ E	arenosols gleyic	undisturbed	16. 7. 2019
14	73° 25′ 30.4″ N, 75° 44′ 22.0″ E	arenosols protic	undisturbed	18. 7. 2019
15	73° 25′ 44.0″ N, 75° 41′ 17.5″ E	fluviosols tidalic	undisturbed	18. 7. 2019
16	73° 26′ 09.1″ N, 75° 41′ 58.0″ E	fluviosols gleyic	undisturbed	18. 7. 2019
17	73° 26′ 10.7″ N, 75° 41′ 53.3″ E	arenosols protic	undisturbed	18. 7. 2019
18	73° 26′ 57.1″ N, 75° 43′ 26.0″ E	arenosols protic	undisturbed	18. 7. 2019
19	73° 26′ 56.2″ N, 75° 43′ 33.4″ E	fluviosols gleyic	undisturbed	18. 7. 2019
20	73° 27′ 26.0″ N, 75° 44′ 05.1″ E	arenosols gleyic	undisturbed	18. 7. 2019
21	73° 31′ 10.3″ N, 75° 51′ 19.0″ E	sands	undisturbed	19. 7. 2019
22	73° 30′ 37.0″ N, 75° 50′ 10.5″ E	sands	undisturbed	19. 7. 2019
23	73° 30′ 20.0″ N, 75° 41′ 08.2″ E	arenosols gleyic	undisturbed	20. 7. 2019
24	73° 30′ 25.9″ N, 75° 41′ 00.2″ E	arenosols protic	undisturbed	20. 7. 2019
25	73° 28′ 42.7″ N, 75° 37′ 35.8″ E	arenosols protic	undisturbed	20. 7. 2019
26	73° 28′ 43.4″ N, 75° 37′ 26.4″ E	fluviosols gleyic	undisturbed	20. 7. 2019
27	73° 29′ 15.1″ N, 75° 40′ 45.2″ E	arenosols protic	undisturbed	20. 7. 2019
28	73° 29′ 15.5″ N, 75° 40′ 48.7″ E	arenosols gleyic	undisturbed	20. 7. 2019
29	73° 29′ 54.4″ N, 75° 42′ 46.0″ E	arenosols protic	undisturbed	20. 7. 2019
30	73° 29′ 52.6″ N, 75° 42′ 50.3″ E	arenosols gleyic	undisturbed	20. 7. 2019
31	73° 30′ 05.0″ N, 75° 43′ 06.1″ E	arenosols protic	undisturbed	20. 7. 2019
32	73° 30′ 38.6″ N, 75° 45′ 07.1″ E	arenosols gleyic	disturbed	21. 7. 2019
33	73° 30′ 56.2″ N, 75° 46′ 03.4″ E	arenosols gleyic	disturbed	21. 7. 2019
34	73° 26′ 29.5″ N, 75° 42′ 27.0″ E	lake bottom sediments	undisturbed	18. 7. 2019
35	73° 30′ 19.9″ N, 75° 41′ 09.2″ E	lake bottom sediments	undisturbed	20. 7. 2019
36	73° 29′ 15.5″ N, 75° 40′ 49.3″ E	lake bottom sediments	undisturbed	20. 7. 2019
37	73° 26′ 04.8″ N, 75° 52′ 15.0″ E	lake bottom sediments	undisturbed	16. 7. 2019
38	73° 31′ 05.9″ N, 75° 43′ 48.7″ E	coastal marine sediments	undisturbed	20. 7. 2019
39	73° 31′ 04.2″ N, 75° 43′ 25.9″ E	coastal marine sediments	undisturbed	20. 7. 2019

Table 2 Soil and sediments quality indices and their categorization

Index	Value	Classification
CF (Hakanson 1980)	CF< 1	low pollution
	1≤ CF< 3	moderate pollution
	3≤ CF< 6	high pollution
	CF ≥6	extremely high pollution
Igeo (Muller,1981)	Igeo≤ 0	uncontaminated
	0< Igeo <1	uncontaminated to moderately contaminated
	1< Igeo <2	moderately contaminated
	2< Igeo <3	moderately to heavily contaminated
	3< Igeo <4	heavily contaminated
	4< Igeo <5	heavily to extremely contaminated
	Igeo ≥5	extremely contaminated

3 Results and discussion

3.1 *Physico-chemical parameters and organic matter content*

The basic physical and chemical characteristics of the samples are given in Table 3.

The pH_{H_2O} of the studied soils and sediments was predominantly neutral. The average values of disturbed and undisturbed soils, lake and marine sediments differ little from each other with a variation range from 6.42 to 6.60 (Table 2). Arenosols gleyic were the most acidic in waterlogged areas, in the surface horizon of which the pH_{H_2O} value in some cases decreases to 4.8. These were the most common soils of the island (more than 50% of the territory that is not flooded by regular tides). Arenosols protic (the second type of soil by area) occupy the top positions in the relief and have neutral pH_{H_2O} varying from 6.1 to 7.1. In the anthropogenically disturbed soils, where the production of organic acids was lower due to vegetation disturbance, the pH_{H_2O} values were higher than in the undisturbed soils and averaged 6.6 units.

The soil texture was predominantly sandy. The proportion of sand size fraction (defined as 50 to 2,000 µm) varied from 45 to 96%, silt size fraction (2–50 µm) – from 0 to 9.5%, and clay size fraction (<2 µm) – from 0.4 to 38%. The average values were 79.8, 8.2 and 12.0%, respectively. Fractions of fine sand (50–200 µm) and medium sand (200–500 µm) predominated in the sand fraction. An example of particle size distribution in horizons of different soil types is presented in Table 4.

There was an increase in the proportion of clay and silt size fractions with depth. The average content of clay in the soil surface horizons was 6.1%, while in the middle and lower part of the profile it was increasing to 16.7%.

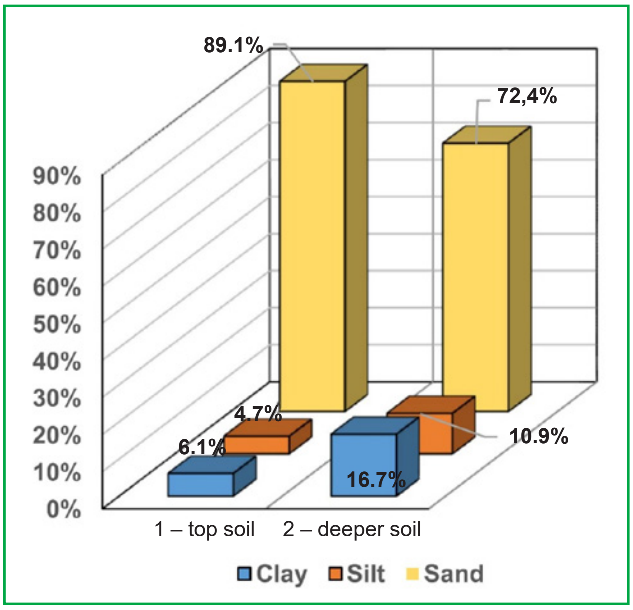

Figure 2 Distribution of clay, silt and sand size fractions in soils at different depths

Table 3 Physiochemical characteristics of the soils and sediments (mean ±SD)

Type of object	pH	Conductivity (µS/cm)	TC (%)	TN (%)	TC : TN
Undisturbed soils	6.48 ±0.38	159 ±325	1.6 ±5.0	0.07 ±0.26	22.3
Soils of anthropogenic sites	6.60 ±0.35	49.5 ±22.2	0.91 ±0.62	0.05 ±0.07	18.6
Lake sediments	6.58 ±0.39	177 ±79	0.36 ±0.42	0.010 ±0.019	38.1
Marine sediments	6.42 ±0.16	8.2 ±0.4	4.9 ±6.4	0.56 ±0.79	8.7

Table 4 Particle-size distribution at different depths in some studied soil profiles, Vilkitskiy Island

Soil	Depth (cm)	Clay	Fine-Silt	Middle-silt	Coarse-silt	Fine-sand	Middle-sand	Coarse-sand
		<2.0 µm	2–5 µm	5–20 µm	20–50 µm	50–200 µm	200–500 µm	500–2000 µm
№1, Arenosols protic	0–5	8.8%	ND	ND	1.36%	22.97%	60.87%	5.96%
	15–20	0.1%	1.08%	0.71%	2.04%	21.77%	67.53%	6.78%
	35–40	30.89%	3.29%	5.94%	9.48%	37.93%	11.74%	0.73%
№2, Arenosols gleyic	0–5	ND	0.01%	3.25%	1.50%	27.07%	62.19%	5.98%
	20–25	38.1%	3.60	6.76%	6.05%	33.85%	10.93%	0.70%
№3, Arenosols protic	0–5	1.44%	0.95%	1.24%	1.43%	23.50%	65.02%	6.42%
	15–20	2.04%	0.35%	1.23%	2.44%	20.89%	66.33%	6.72%
№4, Arenosols gleyic	0–5	14.26%	1.49%	0.10%	7.63%	61.61%	14.11%	0.81%
	15–20	12.30%	1.19%	2.68%	7.59%	60.41%	14.95%	0.87%

ND – not derermined

The proportion of the silt size fraction was also increasing with the depth, while the proportion of the sand size fraction was significantly decreasing from 89.1% to 72.4% (Figrue 2).

The carbon content in the soils varied from 0.05 to 30.2%. The maximum carbon content was determined in Arenosols gleyic while in Arenosols protec the TC content was lower than 1%. TC content in the upper organic horizons was 3.7 times higher than in the deeper mineral horisons. Similar distribution was also characteristic for the total nitrogen content: in the top soil the average TN content was 0.1%, while in the dipper horizons it was only 0.03%. In many cases, however, distribution of the organic matter was violated by cryogenic soil mixing: in 9 profiles, the maximum TC content was measured in deeper horizons. Active cryogenic mixing of soil with disrurbance of the boundaries of soil horizons and changes in carbon distribution was previously noted in the soils of the Arctic archipelago Franz Josef Land (Nikitin et al., 2020). The ratio TC to TN, with rare exceptions, was in the range of 10–25 with the average value being 21.7 for upper horizons and 19.0 for mineral deeper horizons. The lake sediments were characterized by an extremely low TN content (0.01%), and the highest ratio TC to TN, while in the marine sediments the nitrogen content was the highest, and the average TC to TN ratio was the lowest (TC : TN = 8.7). Low values of TC : TN were previously observed on the seaside terraces of Bely Island in the Kara Sea (Moskovchenko et al., 2017), which indicates an intensive biological cycle of periodically flooded areas during tides.

3.2 Concentrations of THg

Descriptive statistics of THg content in the soils and lake/marine sediments are shown in Table 5.

The minimum mercury content was found in lake sediments (on average 3.8 ng/g). The THg content reached the maximum of 31.2 ng/g in the sediments of the coastal part of the sea. In undisturbed soils, the average Hg content was 6.4 ng/g and varied in the range from 1 to 36.6 ng/g. There were significant differences in mercury content depending on the particle size disstibution and the presence of peat horizon on the surface. The minimum values were found in sandy Arenosols protic, which occupy drained watersheds. There the mercury content did not exceed 10 ng/g. Loamy soil horizons contained 3.5 times more mercury than sandy horizons (Figure 3). In Arenosols gleyic soils of swampy wetlands the top soil was peat from 3 cm to 5 cm thick where the mercury content varied in the range of 14.7–36.6 ng/g, and where the median value was the largest of all the studied soils (Figure 3).

Factors that control the distribution of THg in the soils of Vilkitsky Island were assessed on the basis of correlation analysis. The calculation showed that the mercury

Table 5 Statistical summary of THg content in the soils and sediments of Vilkitskiy Island

Type of object	n	mean	median	SD	Min-max
Undisturbed soils	67	6.4	3.4	6.7	1–36.6
Soils of anthropogenic sites	20	18.4	8.1	21.4	1.5–65.4
Lake sediments	5	3.8	3.7	1.9	2.0–5.8
Marine sediments	2	31.2	31.2	7.8	25.7–36.7

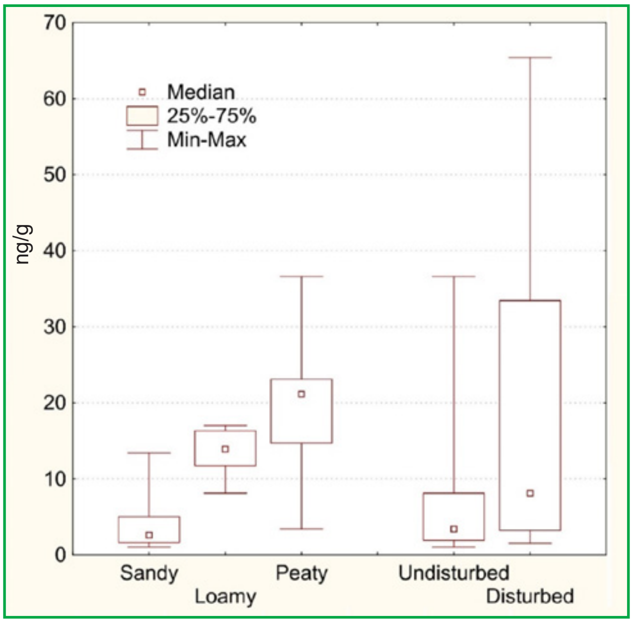

Figure 3 Statistical indicators of mercury content in the sandy, loamy and peat soil horizons, undisturbed and disturbed soils

content in the soils was directly related to the content of clay and silt texture particles (*R* = 0.95 and 0.70, respectively). The total carbon and nitrogen content, pH value and electrical conductivity had little effect on the mercury content. The correlation of THg content and the total carbon, and total nitrogen content was positive, but statistically insignificant (*R* = 0.21–0.24). The mercury content was increasing with the decrease in pH but the correlation was weak (Table 6). The negative correlation was probably due to the fact that the peat horizon was formed in the conditions of waterlogging, in which the THg content was increased compared to the sandy soils.

The calculated THg stocks in undisturbed soils (layer 0–20 cm) varied in the range of 0.28–3.4 mg/m^2 with an average value of 1.45 ±1.1 mg/m^2 (n = 32). Similar values were obtained in the polar regions of Sweden, where the mercury stocks in the upper 40 cm of the soil averaged 4.4 ±1.3 (Klaminder et al., 2008), or, in terms of the upper 20 cm, as in our study, <2.2 mg/m^2. Higher stocks were found in the soils of Shule River Basin, Tibetan Plateau (Sun et al., 2017) and Bathurst Island, High Arctic of Canada (Givelet et al., 2004), which, in terms of 20 cm, were 3.4 and <3.5 mg/m^2, respectively. In the lake sediments of Vilkitsky Island mercury stock was around the same as in soils (on average 1.2 mg/m^2 in the 0–20 cm layer). The maximum stock of mercury was found in coastal sediments (6.2–8.8 mg/m^2).

THg stocks in the soil top horizons were lower than in the deeper ones since the higher mercury content in the upper peat horizons was compensated by the higher bulk density of the lower mineral layers. The stock of mercury in the 0–5 cm layer varied from 0.008 to 0.34 µg/m^2, while in the 15–20 cm layer it was from 0.16 to 4.2 µg/m^2. For the same reason, there was no correlation between mercury stocks and the content of total carbon or nitrogen (*R* = -0.15 and -0.16, respectively). Increased stocks of mercury in the deeper horizons were negatively correlated to the soil nitrogen and carbon content. Mercury stocks were the lowest in the sandy soils, where in the upper 20 cm layer they rarely exceed 1 mg/m^2, and the highest in the loamy soils of lake terraces, where they reached 3.4 mg/m^2. At the same time, the mercury content in the marine sediments depended on the content of TC and TN, which was 3 or more times higher than in the soils and lake sediments (see Table 3). It was previously noted that marine sediments accumulate mercury more intensively than lake sediments as a result of association with particles rich in organic matter (Fitzgerald et al., 2007). The dependence of mercury content in polar and high-altitude soils on the content of organic matter and soil texture was repeatedly noted in previous studies. In Spitzbergen it was shown that THg was accumulated in the upper soil layer and strongly correlated with the soil organic matter (Halbach et al., 2017). In the soils of Tibet, a strong positive relationship was observed between the concentration of THg, the content of organic carbon and the amount of silt, indicating that the content of organic matter and the silt fraction were the two dominant factors affecting the spatial distribution of THg (Sun et al., 2017).

Table 6 Spearman's rank correlation coefficients between THg content, THg stock and other measured soil parameters

Characteristics	THg concentration	THg stock in layer 0–20 cm
TC	0.21	-0.06
TN	0.24	-0.10
pH	-0.16	0.16
Conductivity	0.30	0.16
Clay	0.95	0.57
Silt	0,70	0.55
Sand	-0,98	-0.62

In Alaska soils, the maximum mercury content was also found in organic horizons (Olson et al., 2018). The ability to form complexes with organic matter is one of the main geochemical fitches of mercury (Kabata-Pendias 2010). It was noted that in the soils of Antarctica organic matter is one of the most important environmental components for binding Hg and concentrations of Hg in peat mats significantly correlated to organic C concentrations (Bargagli et al., 2007).

In the upper part of the Earth's crust, the THg content is 50 ng/g (Rudnick, Gao, 2003); the average Hg content in the Earth's soils is 1.1 µg/g (Kabata-Pendias, 2010). This values are significantly higher than the values obtained in our study. Previous studies conducted in the north of Western Siberia revealed a higher level of Hg content in soils compared to our data. One of the first studies showed that the average Hg content in sandy soils was 9 ng/g, in tundra gley soils – 55 ng/g, and the maximum content of 200 ng/g was typical for peat soils (Dorozhukova et al., 2000). Similar results were later obtained by Opekunova et al. (2019): the average mercury content in the upper organic horizons of the soils in the northern regions of Western Siberia was 79 ng/g, in the lower mineral horizons – 20 ng/g, and in peat horizons – 100 ng/g. Thus, according to our results, the maximum Hg content was observed in peat horizons of the soils. Results similar to ours were obtained when studying the composition of sediments of two Arctic lakes in Western Siberia, in which the mercury content was 4.3–5.2 ng/g (Tatsii and Baranov, 2022).

Thus, the soils and lake sediments of Vilkitsky Island contain a low amount of mercury. The comparison with data for other remote areas of the Arctic, which are shown in Table 7, confirmed that the soils and lake sediments on Vilkitsky Island are characterized by a low mercury content. Only in the soils of Greenland and Knudsenheia, Ny-Alesund, the THg content was comparable to Vilkitsky Island, in all the other regions the mercury content was higher. The data on the minimum mercury content in the soils of the Russian Arctic, amounting to 40 ng/g (AMAP, 2005), should be adjusted downward.

It is also of interest to compare the results obtained in this study with the results received for the mountain soils of Asia, remote from industrial areas. Ombrotrophic peatlands of the Hinggan Mountains (Northeast China) are regarded as one of the faithful archives of atmospheric mercury deposition. In the soils of Tibet, the total mercury content varied from 6.3 to 29.1 ng/g (Sun et al., 2017). Thus, the Hg content in the peat of Vilkitsky Island is very close to the values obtained in the areas remote from sources of industrial emissions and can be considered background.

The reasons for the low mercury content in the soils of the island are to be discussed. The supply of mercury in soils depends on natural and anthropogenic sources. In mineral horizons, a significant amount of Hg results from its release from natural geologic sources (Obrist et al., 2018). The sandy sediments that make up the island are characterized by low mercury content. According to Voitkevich et al. (1990), sandy sediments contain an order of magnitude less mercury than clay sediments (3 and 40 ng/g, respectively). Therefore, one of the main reasons for low mercury content is the predominance of sandy sediments, in which mercury content is low.

However, Hg accumulation and retention in soil are also determined by soil morphology and genesis as well as soil

Table 7 Comparison of THg content in the soils and sediments between Vilkitskiy Island and some other circumpolar Arctic areas

Area	THg (ng/g)	Reference
Vilkitskiy Island	1–36.6	our data
Greenland	from <10 (Tasiilaq lake area) up to 30 (Qaqortoq lake area)	Riget et al. (2000)
Canadian High Arctic	10–250	Loseto et al. (2004)
Russian Arctic	40–150	AMAP (2005)
Hudson Bay	8–58	Hare et al. (2010)
Alaska	151 (organic horizons) 98 (mineral horizons)	Olson et al. (2018)
Knudsenheia, Ny-Ålesund	0.7–6.6	Jiang et al. (2011)
Ny-Ålesund	210–380	Hao et al. (2013)
Ny-Ålesund	surface soil: 41–254 mineral soil: 4–60	Halbach et al. (2017)
Svalbard	9.1–86.7 (surface sediments)	Liu et al. (2015)

properties, including soil organic matter stability, texture, and pH (Obrist et al., 2018). The low content of mercury in soil of Vilkitsky Island is also likely to be related to the low content of soil organic matter. The dependence of mercury content in soil on the organic matter content has been discussed earlier. Similarly, a decrease in mercury content in Canadian soils was observed in the most northern sites, which has been explained by a decrease in the productivity of biocenoses (Olson et al., 2018).

Nowadays, the Arctic has experienced increased atmospheric Hg inputs compared to the pre-industrial time (Hammerschmidt et al., 2006). Atmospheric transport represents a major pathway of Hg to the Arctic environment (AMAP 2005). We have no data on the amount of atmospheric deposition of mercury on Vilkitsky Island. The nearest site where observations of atmospheric mercury deposition were carried out was near the city of Nadym, approximately 870 km south of Vilkitsky Island. According to the data, the average annual amount of Hg intake from the atmosphere was close to the values obtained in remote unpolluted areas of the Arctic (Eyrikh et al., 2022). On Vilkitsky Island, the intensity of mercury deposition is probably also low, given that it is further away from Nadym and from industrial areas. However, atmospheric mercury depletion events (AMDEs) during polar sunrise are likely to increase THg intake.

The amount of mercury deposited to the surface from the atmosphere in different regions of the Arctic is estimated at 9.2 µg/m^2/year (Obrist et al., 2017), or in the broader range 2.1–11.1 µg/m^2/year (Steinnes and Sjobakk 2005). In Russia, according to Landrs et al. (1998) mercury deposition is 7.1–30.2 µg/m^2/year. Our measured Hg stocks in the upper 0–5 cm layer of soil vary from 8 to 340 µg/m^2 (98 µg/m^2 on average). Thus, in some soils the Hg stock in the upper 5 cm is approximately equal to the annual atmospheric input, while in the others it exceeds it by no more than one order of magnitude. This indicates that the sorption capacity of the studied soils is low and they accumulate mercury extremely poorly. Therefore, it may be assumed that on Vilkitsky Island mercury translocates and accumulates in mainly in the coastal sediments, where THg stocks (on average 7.5 mg/m^2 in the upper 20 cm) are more than five times higher than the average stocks in the soils (1.45 mg/m^2). Translocation of heavy metals from upland soils to coastal and lakeside soils has previously been shown on another Arctic Island, called Beliy (Moskovchenko et al., 2017). An important practical conclusion from this is that if mercury contamination occurs, the maximum impact on living organisms it will cause in the coastal areas of Arctic islands, which should be considered for monitoring purposes.

3.3 Pollution assessment

The average Hg content in the disturbed soils was 18.4 ng/g, which is almost 3 times higher than the content in the undisturbed soils. There were significant differences between the soils of the three investigated sites. At the ship unloading site, the mercury content in the soil was minimal (1.5–2.5 ng/g) and did not exceed background values. On the territory of an abandoned residental area, the mercury content was higher and varied between 1.8–49.4 ng/g (on average 10.8 ng/g), and at the abandoned polar meteorological station mercury content reached the maximum values – 27.8 ng/g on average, varying from 3.7 to 65.4 ng/g. In the surface horizons, the average mercury content was slightly lower than in the deep horizons (the average values were 16.7 and 20.2 ng/g, respectively), which indicated accumulation of mercury in the suprapermafrost horizons. The content of mercury in contaminated areas was on average lower than in the coastal sediments, confirming the earlier conclusion of mercury translocation and subsequent accumulation in the coastal zone.

The average values of CF and Igeo coefficients for different sampling sites are shown in Figure 4.

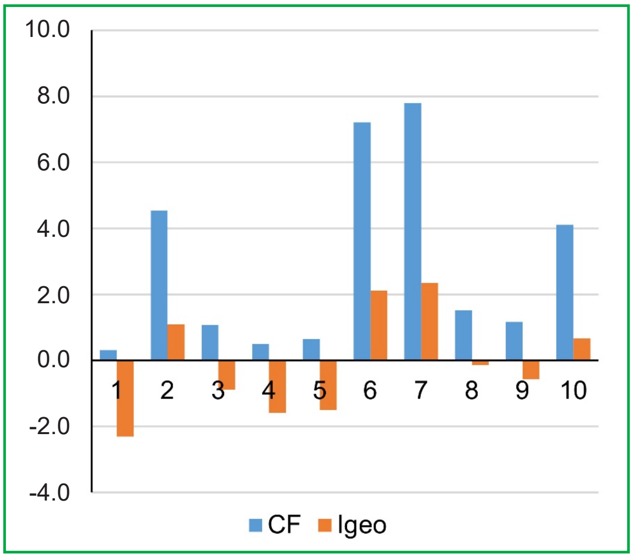

Figure 4 Average CF and Igeo values
1 – coal unloading site, 2–5 – abandoned residential area, 5–10 – abandoned polar station

CF values were maximum on the territory of an abandoned polar meteorological station (sampling sites 6–10), where they varried from 1.2 to 7.8. At the abandoned industrial base, only one sampling site showed a high level of pollution with CF = 4.4. Igeo coefficients indicated the level as «Moderately to heavily contaminated» (2< Igeo< 3) at two sampling sites at the polar station. Sources of mercury intake at the polar station most likely were: coal burning for heating and mercury soil thermometers, which were used during meteorological observations. Coal combustion in thermal power plants is the major anthropogenic source of Hg in the environment (Rai and Maiti, 2019). Thus, mercury pollusion occured in some of the studied soils on a local scale.

4 Conclusions

The THg content in the active layer of the studied soils of Vilkitsky Island varies between 1–36.6 ng/g, which is one of the lowest values for Arctic soils both in Western Siberia and in the polar regions as a whole. The THg concentrations is influenced by acidity/alkalinity levels, particle-size composition and organic matter content. In general, THg were strongly related to the amount of clay and silt particles ($R = 0.95$ and 0.7 respectively). Low THg values were found in sandy soils (Arenosols protic), which form the soil cover of the drained watersheds of the island. Concentrations of TC and TN are a less significant factor for THg accumulation in the studied soils, however, in peat horizons, mercury content is always higher compared to loamy and sandy ones. The highest levels of mercury were found in Arenosols gleyic soils with a relatively thick peat horizon on the surface.

Mercury stocks in the upper 20 cm of soil average to 1.45 mg/m^2 (range 0.28 to 3.4 mg/m^2) and was generally similar to the stocks of another polar and highland regions. Some differences in mercury stocks in topsoil and deeper soil have been observed.THg stocks in the soil top horizons were lower than in the deeper ones since the higher mercury content in the upper peat horizons was compensated by the higher bulk density of the lower mineral layers.

The minimum mercury content was measured in lake sediments (varying from 2.0 to 5.8 ng/g), which is explained by sandy texture of the sediments and extremely low organic matter content. The maximum mercury content (25.7–36.7 ng/g) is observed in loamy coastal marine sediments. In the upper 5 cm layer, mercury stocks range from 8 to 340 µg/m^2. Given that the annual Arctic THg deposition is estimated at 2.1–11.1 µg/m^2/year, in some soils the mercury stock is less than the annual atmospheric input, indicating very low sorption capacity of the soils due to low organic matter content and low content of clay fraction. Consequently, mercury is translocated and accumulates in coastal sediments. To monitor mercury pollution in the Arctic, coastal areas should be the most informative site.

Local mercury contamination has been detected on the island. In disturbed soil, the THg content is approximately 3 times higher than in the undisturbed soils. The highest concentrations were measured in the soils of the abandoned polar meteorological station, which is associated with the use of coal for heating, and also, probably, with the use of soil mercury thermometers for the meteorological site. According to CF and Igeo coefficients, the level of contamination was at the polar station was “moderately to heavily“ (2< Igeo< 3). The pollution is local in scale, undisturbed soils can be considered as a reference for the background THg concentration in soils of the Arctic.

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