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THE CONTENT OF HEAVY METALS AND SULFUR IN FOREST ECOSYSTEMS IN THE PECHENGANIKEL SMELTER'S ZONE OF IMPACT DUE TO THE REDUCTION OF ATMOSPHERIC EMISSIONS[1]

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Abstract. The relevance of the study is determined by the need to study the state of forest ecosystems in conditions of changing anthropogenic pressure and the practical significance of improving the monitoring system for sustainable forest management. The dynamics of the intake of pollutants with atmospheric precipitation, their accumulation in the soil and tree layer (using the example of an edificator species – Pinus sylvestris L.) with prolonged anthropogenic impact on forest ecosystems, as well as during the period of a sharp reduction in atmospheric emissions in the impact zone of the Pechenganikel smelter (Nickel settlement, Murmansk region). The studies were carried out in the period from 1991 to 2021 on the permanent monitoring plots located in pine forests at various distances from the source of atmospheric emissions (7, 14, 44 km). Between 1991 and 2020, the annual volume of industrial emissions of SO_2, Ni and Cu into the atmosphere decreased. In December 2020, the release of pollutants into the atmosphere practically stopped due to the Pechenganikel metallurgical smelter being shut down. First of all, a sharp reduction in the emissions of pollutants into the atmosphere led to a change in the composition of snow and rainwater, the concentrations of pollutants (Ni, Cu, Co, Pb и Cd) in them approached regional background values. However, the concentrations of heavy metals and sulfur in the soil are still significantly higher than in typical forest ecosystems of the Murmansk region, due to the long period required for soil regeneration and self-purification.

Keywords: *atmospheric precipitation, soils, Pinus sylvestris, atmospheric pollution, heavy metals, North taiga forests, Arctic*

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The Murmansk region is one of the most industrially developed areas of the Russian Arctic, belonging to the number of Russian regions whose forest ecosystems are the most sensitive to environmental pollution. The specificity of ecosystem functioning is determined, on the one hand, by the natural and climatic conditions of the region, on the other hand, by the level of anthropogenic load. The main sources of atmospheric emissions of acidifying substances and heavy metal compounds in the region are the enterprises of Kola Mining and Metallurgical Company JSC (Severonickel and Pechenganickel), whose activities have caused degradation of forest ecosystems in large areas. The consequence of long-term technogenic pollution from industrial enterprises was the accumulation of heavy metals in various components of terrestrial and aquatic ecosystems (Lukina, Nikonov, 1996; Kashulina et al., 2014; Lyanguzova et al., 2014; Lyanguzova et al., 2015; Koptsik et al., 2016; Dauwalter, Kashulin, 2018). Works on studying the state of ecosystems under the impact of atmospheric emissions from industrial enterprises are carried out by many domestic and foreign scientists, including in the conditions of reduction of technogenic load (Chernen'kova et al., 2014; Vorobeichik et al., 2014; Hale, Robertson, 2016; Kowalska et al., 2016; Shergina et al., 2018; Zakrzewska, Klimek, 2018; Mikhailova, 2020; Vorobeichik, 2022). But there is insufficient information to assess the response of forest ecosystems and their components to the reduction of anthropogenic load due to the closure of an industrial facility.

For more than 80 years (since 1940) the Pechenganikel copper-nickel smelter (Nickel settlement, Zapolyarny town) has been operating in the northwestern region – a source of sulfur dioxide and polymetallic dust, contributing to the formation of heavy non-ferrous metals (Ni, Cu, Co, Cd, Pb, etc.). Studies of forest ecosystems in the impact zone of the combine indicate a significant accumulation of pollutants in soils, plants, changes in biogeochemical cycles of elements, life state of stands (Current..., 2008; Kola..., 2012; Evdokimova et al., 2014; Isayeva, Sukhareva, 2021). In December 2020, a uniquely significant event took place — the closure of the

[1] The work was carried out within the framework of the state assignment of *Institute of Industrial Ecology Problems of the North, Kola Scientific Center of the Russian Academy of Sciences*

smelting shop (Nickel settlement), which resulted in a sharp decrease in air pollutant emissions. In this regard, the study of the current state of northern taiga forests in the zone of prolonged anthropogenic impact in the initial period after the reduction of atmospheric emissions is particularly important for assessing the state of forest ecosystems, forecasting the dynamics of biogeochemical cycles and sustainable functioning of forests, comparing the level of pollutant deposition with atmospheric precipitation with the level considered critical for forest ecosystems.

The aim of the study is to analyze the dynamics (1991—2022) of heavy metals and sulfur content in atmospheric deposition, soil and vegetation cover of pine forests in the zone of impact of atmospheric emissions from the Pechenganickel smelter, (Murmansk region).

OBJECTS AND METHODOLOGY

The research was conducted in the north-west of Murmansk region, in the northern taiga subzone, in the period from 1991 to 2022 on permanent monitoring sample plots (PMP) located along the pollution gradient from the Pechenganickel smelter at 7, 14, 44 km. The sample plots were established within the framework of The Lapland Forest Damage Project (1990—1995), in which staff of the Institute of Industrial Ecology Problems of the North of the Kola Scientific Center of the Russian Academy of Sciences and the Forest Research Institute of Finland participated. In the course of these studies, a monitoring network of sites was established from Nickel settlement to Finland along three transects (Lukina, Nikonov, 1993, 1996). This paper presents the results from the sample sites located in the Russian Federation and located in the southwestern direction from the smelter.

The main vegetation type in the study area is lichen-shrub pine forests in automorphic landscape positions on illuvial-iron podzols (Rustic Podzols, WRB2022) with a typical profile: O-E-BHF (BF, BH)-C. The tree layer is dominated by pine (*Pinus sylvestris* L.), which varies in age from 80 to 260 years. The ground cover is dominated by shrubs — blueberry (*Vaccinium myrtillus* L.), cowberry (*Vaccinium vitis-idaea* L.), crowberry (*Empetrum hermaphroditum* Hager.) and the lichen (*Cladonia stellaris* (Opiz) Pouzar&Vezda). The background area is located at a considerable distance from the source of pollution (275 km) in the south-west of Murmansk region in a lichen-shrub pine forest and is represented by 2 stationary sample plots, which reflect the regional background and meet all international criteria of control plots (UNECE ICP Forests Programme..., 2020).

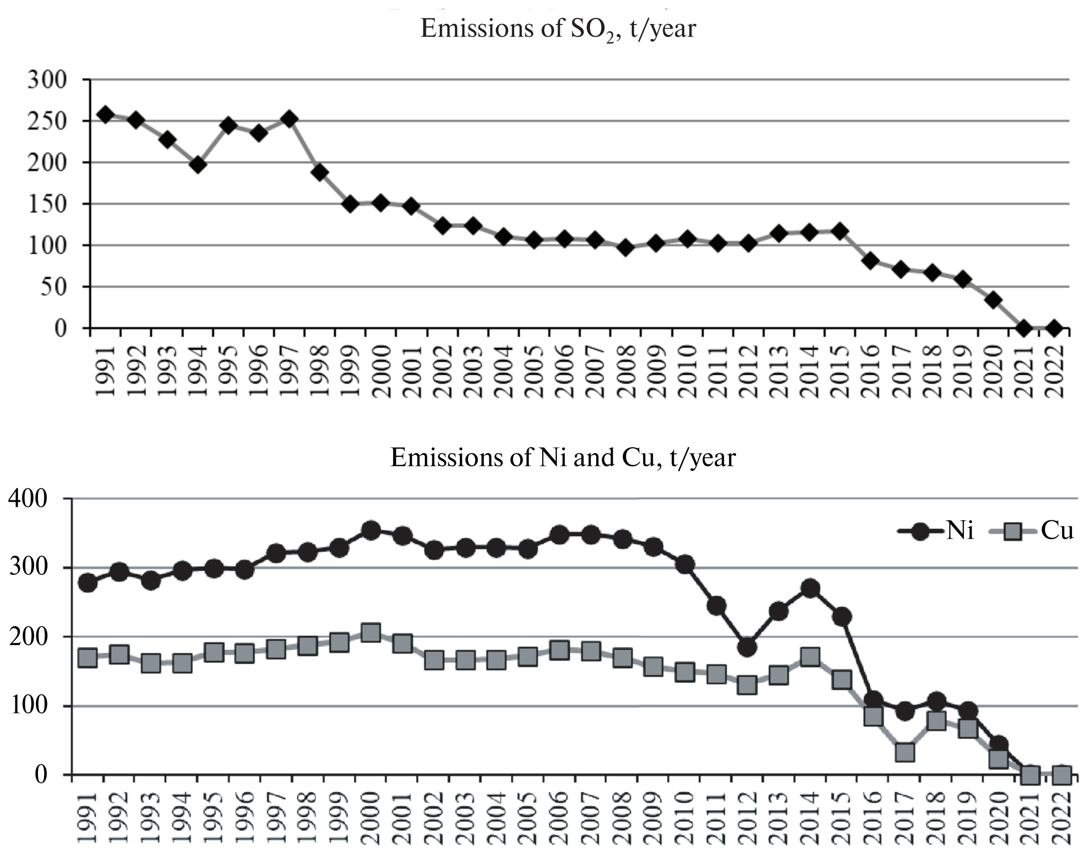

Fig. 1. SO_2, Ni, Cu emissions by Pechenganickel smelter (based on the data of Kola MMC for the period 1991—2022).

The closure of the smelting shop of the Pechenganickel smelter in December 2020 contributed to a significant reduction of air pollutant emissions by Kola MMC enterprises (Sukhareva et al., 2020; Annual Report..., 2021). According to the information of JSC Kola MMC provided by *Institute of Industrial Ecology Problems of the North, Kola Scientific Center of the Russian Academy of Sciences*, during the study period annual SO_2 emissions by Pechenganickel smelter decreased from 257.5 thousand tons in 1991 to 0.1 thousand tons in 2022 (Fig. $1_)$. Annual Ni and Cu emissions in 1991 were 279 tons and 171 tons, in 2022—2.1 tons and 0.5 tons, respectively.

Snow was sampled in 2004, 2005, 2021 and 2022, and rain in 2004, 2005 and 2021. Snow was collected from the undisturbed trench wall using a plastic collector during the period of maximum snow accumulation (late March — early April) under the forest canopy and in the open area in triplicate. In each sample area, 15 rain collectors were used for rainwater collection (12 under the forest canopy, 3 in the open area), sampling carried out monthly between June and October, measuring the volume of precipitation in each collector and taking one mixed sample for analysis. Deposition of the main pollutants with precipitation was calculated taking into account the average annual concentration and average annual sample volume.

Soil samples were collected in 2004, 2011, 2019, 2021 at the PMP in 3—5-fold repetition at the end of the growing season (August). Samples were collected by soil horizons: litter/organogenic horizon (OL, OF, OH), eluvial horizon (E), illuvial horizon (B), and soil-forming rock (C). Soil samples were sieved through a sieve with 1 mm holes.

Pine needles were sampled in 1991, 2004, 2011, 2019 from the upper third of the crown in 5—15-fold repetition at the end of the growing season (August). In the laboratory, needles were divided into current year, annual and perennial needles. The limiting age of perennial pine needles was 4—6 years on all studied PMPs.

Actual acidity (pH) in soil samples in aqueous suspension was determined at a soil: solution ratio of 1:25 for organogenic and 1:1.25 for mineral horizons. To determine the concentration of mobile forms of element compounds, soil samples were treated with 1M CH_3COONH_4 (pH = 4.65) (Methods..., 1989). The same soil to displacer ratios were used as for pH determination. Concentrations of chemical elements in needles were determined after decomposition with concentrated HNO_3 (wet ashing)

Actual acidity (pH of water extract) of snow, rainwater and soil samples was measured potentiometrically. Concentrations of metals (Cu, Ni, Pb, Cd, Cr, Co) in all samples were determined by atomic absorption spectrometry; S in soils and plants — by turbidimetric method, SO_4^{2-} in snow and rainwater — by ion-exchange chromatography. Analytical studies were carried out at the Center for Collective Use of Physical and Chemical Methods of Analysis of the Institute of Industrial Ecology Problems of the North of the Federal Research Center Kola Science Center.

A total of 754 samples were analyzed during the study period (1991—2022), of which 249 were atmospheric deposition, 235 were soils, and 270 were pine needles.

The obtained data were processed by statistical methods using MS Excel software (descriptive statistics) and Statistica 13.3 (Mann-Whitney U-test).

RESULTS AND DISCUSSION

Snow. During the period of intensive operation of the smelter (2004—2005), a significant ($p<0.05$) increase in snow water concentrations of Ni (up to 19.5 times), Cu (up to 12 times) and Co (up to 7 times) was observed at the PMPs at 7 and 14 km from the smelter compared to the PMP at 44 km both under the forest canopy and in the open area (Table 1). Acidity was higher at the 44 km PMP than at PMPs located 7 and 14 km away. Moreover, at 44 km from the pollution source, concentrations of Ni, Cu, Co, Pb and Cr (2 to 15 times) and SO_4^{2-} (up to 5 times) increased significantly ($p<0.05$) in snow under the forest canopy compared to the background area. At the PMPs located 14 and 7 km from the smelter, the concentrations of heavy metals under the forest canopy increased for Co, Cd, Pb, Cr — 2 to 12 times, and for Cu and Ni — 66 and 185 times, for sulfates — up to 4 times compared to the background, which indicates a significant technogenic load on forest ecosystems exerted by the smelter during this period. An increase in acidity was observed on all the studied PMP compared to background values.

During the period of sharp decrease in emissions (2021—2022), a significant increase in SO_4^{2-} concentrations (up to 3 times) relative to the regional background values (Table 1) is detected at all studied PMPs in the open area. At the PMP at 7 km from the smelter under the forest canopy, an increase ($p < 0.05$) in snow water concentrations of Co and Cd (up to 6 and 2 times, respectively) is observed compared to the PMP at 44 km from the pollution source. Concentrations of sulfates at the PMP at 14 km from the source of pollution under the forest canopy SO_4^{2-} — 1.5 times reliably ($p < 0.05$) higher than in the open area.

Comparing the period of the smelter closure with the period of its active operation (2021—2022), it should be noted a reliable ($p<0.05$) decrease in the concentrations of heavy metals in snow both under the forest canopy and in the open area. In 2021—2022 at the PMP, 44 km away from the pollution source, the concentrations of Ni, Cu, Co, Cd, Pb and Cr decreased from 2 to 47 times, at 14 and 7 km — from 3 to 80 times compared to 2004—2005. A decrease in the acidity of snow water was detected at all investigated PMPs. This indicates the reduction of technogenic load on forest ecosystems after the closure of the smelting shop of the smelter.

Table 1. Concentrations of Ni, Cu, SO_4^{2-} (mg/l), Co, Pb, Cd, Cr (μg/l) and pH in snow water at PMPs located at different distances from the Pechenganickel smelter

Periods	Position	pH	Ni	Cu	SO_4^{2-}	Co	Cd	Pb	Cr
2004—05	Background area 275 km								
	Under the canopy	4.83 0.05	0.0002 0.0001	0.001 0.0001	0.43 0.07	0.07 0.02	0.08 0.02	0.12 0.03	0.10 0.01
	Open area	No data							
	44 kilometers								
	Under the canopy	4.41 0.09	0.003 0.001	0.007 0.002	2.22 1.13	0.16 0.06	0.04 0.01	0.90 0.20	0.37 0.08
	Open area	4.47 0.08	0.002 0.001	0.006 0.002	1.30 0.50	0.13 0.03	0.04 0.01	0.94 0.24	0.37 0.09
	14 kilometers								
	Under the canopy	4.56 0.08	0.037 0.020	0.066 0.031	1.78 0.33	0.87 0.35	0.18 0.07	1.48 0.34	0.30 0.09
	Open area	4.62 0.07	0.034 0.018	0.072 0.036	1.51 0.17	0.89 0.45	0.18 0.09	1.66 0.37	0.38 0.11
	7 kilometers								
	Under the canopy	4.59 0.10	0.036 0.014	0.048 0.017	1.68 0.40	0.76 0.26	0.09 0.02	1.57 0.53	0.40 0.06
	Open area	4.59 0.10	0.039 0.015	0.054 0.022	1.75 0.43	0.71 0.30	0.10 0.03	1.49 0.47	0.35 0.07
2021—22	Background area 275 km								
	Under the canopy	5.24 0,08	0.003 0.001	0.0004 0.0002	1.64 0.89	0.01 0.003	0.01 0.001	0.04 0.01	0.08 0.02
	Open area	5.46 0.11	0.002 0.001	0.0004 0.0001	0.52 0.08	0.01 0.000	0.01 0.001	0.01 0.003	0.03 0.002
	44 kilometers								
	Under the canopy	5.72 0.21	0.001 0.000	0.001 0.0002	1.36 0.23	0.01 0.003	0.01 0.001	0.03 0.01	0.15 0.03
	Open area	5.61 0.25	0.004 0.002	0.0004 0.0002	1.06 0.23	0.02 0,005	0.01 0.001	0.02 0.01	0.16 0.11
	14 kilometers								
	Under the canopy	5.41 0.11	0.003 0.001	0.001 0.0003	1.49 0.13	0.03 0.01	0.01 0.001	0.04 0.01	0.06 0.01
	Open area	5.56 0.21	0.002 0.001	0.002 0.001	1.01 0.11	0.03 0.01	0.01 0.003	0.02 0.01	0.05 0.01
	7 kilometers								
	Under the canopy	5.43 0,13	0.003 0.001	0.001 0.0004	1.50 0.10	0.06 0.04	0.02 0.003	0.02 0.01	0.11 0.04
	Open area	5.52 0.20	0.013 0.008	0.001 0.0004	1.51 0.15	0.01 0.002	0.01 0.002	0.02 0.01	0.08 0.02

Note. Here and in Tables 2—5, the numerator is the mean value and the denominator is the standard error.

Table 2. Concentrations of Ni, Cu, SO_4^{2-} (mg/l), Co, Pb, Cd, Cr (μg/l) and pH in rainwater at PMPs located at different distances from Pechenganickel smelter

Periods	Position	**pH**	**Ni**	**Cu**	**SO_4^{2-}**	**Co**	**Cd**	**Pb**	**Cr**
2004—05	Background area 275 km								
	Under the canopy	4.75	0.001	0.005	1.39	0.13	0.06	0.33	0.49
		0.21	0.0002	0.001	0.26	0.04	0.02	0.09	0.13
	Open area	No data							
	44 kilometers								
	Under the canopy	4.72	0.004	0.004	2.53	0.24	0.03	0.30	0.19
		0.32	0.001	0.001	0.53	0.02	0.01	0.04	0.04
	Open area	4.61	0.002	0.002	0.97	0.18	0.01	0.29	0.13
		0.11	0.0001	0.0002	0.10	0.07	0.00	0.06	0.03
	14 kilometers								
	Under the canopy	4.75	0.021	0.020	2.22	0.55	0.14	0.83	0.28
		0.13	0.005	0.006	0.45	0.14	0.04	0.14	0.04
	Open area	4.66	0.011	0.015	1.25	0.28	0.07	0.69	0.28
		0.10	0.004	0.005	0.30	0.10	0.02	0.17	0.06
	7 kilometers								
	Under the canopy	4.62	0.052	0.052	2.71	1.39	0.16	0.68	0.34
		0.22	0.008	0.013	0.35	0.19	0.03	0.16	0.05
	Open area	4.70	0.031	0.032	1.82	0.79	0.07	0.46	0.29
		0.31	0.006	0.008	0.33	0.09	0.02	0.11	0.07
2021—22	Background area 275 km								
	Under the canopy	5.64	0.002	0.002	1.46	0.25	0.03	0.22	0.19
		0.16	0.001	0.001	0.27	0.06	0.01	0.08	0.04
	Open area	6.32	0.001	0.002	1.17	0.14	0.01	0.10	0.14
		0.08	0.001	0.001	0.39	0.06	0.002	0.05	0.06
	44 kilometers								
	Under the canopy	4.74	0.002	0.004	2.00	0.01	0.02	0.22	0.17
		0.17	0.001	0.002	0.38	0.00	0.01	0.08	0.04
	Open area	5.09	0.0002	0.004	0.94	0.02	0.01	0.01	0.32
		0.05	0.0001	0.002	0.13	0.01	0.0001	0.00	0.15
	14 kilometers								
	Under the canopy	4.77	0.002	0.003	1.27	0.03	0.01	0.01	0.28
		0.09	0.001	0.001	0.09	0.01	0.00	0.00	0.10
	Open area	5.20	0.000	0.001	0.83	0,01	0.01	0.02	0.49
		0.05	0,000	0.001	0.14	0.004	0.001	0.01	0.16
	7 kilometers								
	Under the canopy	4.80	0.006	0.008	1.73	0.08	0.01	0.11	0.70
		0.18	0.002	0.002	0.22	0.05	0.00	0.07	0.28
	Open area	5.13	0.0004	0.004	0.91	0.03	0.01	0.20	0.20
		0.06	0.0002	0.002	0.06	0.01	0.002	0.19	0.06

Rain. Under the conditions of atmospheric pollution (2004—2005) in rainwater, compared to the background area, the concentrations of Ni up to 4 times) at 44 km from the mill, Ni, Cu, Co, Cd, Pb (from 2 to 50 times) and SO_4^{2-} (from 1.5 to 2 times) at 7 and 14 km from the pollution source are significantly ($p < 0.05$) increased (Table 2). Significant differences ($p < 0.05$) were noted for Cu, Ni and SO_4^{2-} under the forest canopy at 44 km from the smelter; here concentrations are 2 times higher than in the open area. The revealed pattern indicates the washing and leaching of elements from the crowns of woody plants (Lukina and Nikonov, 1996; De Vries et al., 2014; Ershov et al., 2020). When approaching the source of atmospheric pollution (PMP at 7 and 14 km), a reliable ($p < 0.05$) increase in the concentrations of Ni, Cu, Co, Cd, Pb under the forest canopy and in the open area was observed compared to the PMP at 44 km. An increase in SO_4^{2-} concentrations was also detected in the open area (7 km from the smelter) compared to the PMP located 44 km from the smelter.

In 2021, the gradient of atmospheric pollution revealed a significant decrease in the pH indicator compared to the background area. It should be noted that at PMP located 7 km from the mill, the concentrations of Ni and Cu in rainwater under the forest canopy are still higher (3 and 4 times, respectively) than in the background area. At the PMPs located 7, 14 and 44 km from the smelter, SO_4^{2-} and Ni concentrations in rain under the forest canopy are significantly ($p < 0.05$) higher than in the open area. In addition, rainwater at 7 km shows a significant increase in Ni concentrations (up to 3 times) under the forest canopy compared to the PMP at 44 km

Comparison of the smelter closure period with the period of its active operation showed a decrease ($p < 0.05$) of heavy metal concentrations in rain: at 44 km from the smelter, Co concentrations under the forest canopy decreased 23 times, Ni and Pb concentrations in the open area — 28 times. Both under the forest canopy and in the open area at the PMP at 14 km the concentrations of Ni, Cu, Co, Pb and Cd decreased from 7 to 62 times, at 7 km — from 6 to 68 times. As in snow water, the significant reduction of heavy metal concentrations in rain indicates the reduction of technogenic load on forest ecosystems after the closure of the smelting shop of the smelter.

Information on the chemical composition of atmospheric deposition is of great indicator value for assessing possible negative impacts on forests. For more than a quarter of a century, the concept of critical loads on forests has been developed, which are defined as “a quantitative assessment of exposure to levels of one or more pollutants below which no significant adverse effects on the most sensitive components of ecosystems are observed, according to the current state of knowledge” (Koptsik, 2004; Critical loads..., 2004; Koptsik et al., 2007). Critical loads are calculated using chemical indicators that define harmful effects and thresholds. For atmospheric deposition, critical loads can be calculated for a specific element, such as sulphate sulphur (Korhola et al., 1999) or heavy metals (Reinds et al., 2006). From the above research results it is established that concentrations of heavy metals and sulfur in atmospheric deposition at the PMP at 7 and 14 km from the source of pollution significantly exceed background values, especially during the period of active operation of the smelting shop of the smelter (2004—2005). Therefore, it is reasonable to compare the levels of pollutant deposition at the objects of the presented studies with the level of critical loads established in international practice.

The critical loads of total deposition (with rain and snow) of $S\text{-}SO_4^{2-}$, Pb, Cd and Cr were not exceeded at all the studied PMPs (Korhola et al., 1999; Reinds et al., 2006, 2008) both during the period of active operation of the smelter and after the smelter closure. The critical load levels for Ni and Cu for Central Lapland ecosystems are 120 and 5 g/ha per year, respectively (Reinds et al., 2006). Ni deposition under the forest canopy and in the open area exceeded the critical load level only during the period of active operation of the smelter 7 km from the pollution source (by a factor of 1.5) (Fig. 2). Cu deposition under the forest canopy and in the open area during the period of intensive operation of the smelter exceeded the level of critical loads for the background area — up to 2 times, at 44 km — up to 4 times, at 14 and 7 km — up to 40 times. After closure of the smelter, Cu deposition in the background area does not exceed the level of critical loads, at the 44 km PMP the exceedance is up to 2 times, at 14 and 7 km — up to 4 times both under the forest canopy and in the open area.

Soils. Soil cover as the most conservative component of an ecosystem determines its state and stability, plays an important role in the formation, maintenance and conservation of biological diversity (Fedorets et al., 2015; World Reference Base..., 2022). The functioning of northern taiga forests is largely determined by the conditions of mineral nutrition of plants, which change significantly in the zone of impact of large industrial enterprises. The organogenic horizon is considered as an effective biogeochemical barrier for heavy metals entering ecosystems as a result of atmospheric pollution (Lukina and Nikonov, 1996; Lyanguzova et al., 2015; Koptsik et al., 2016).

In background forests, the thickness of the organogenic horizon varies from 7 to 12 cm. Background values of actual acidity (pH) of organogenic horizons are characterized by low values and vary in the range from 3.7 to 4.0. Down the soil profile, in mineral horizons, pH values increased, reaching maximum values (5.1—5.2) in the soil-forming rock (horizon C). The maximum content of Ni, Cu, Cd, Pb was observed in the organogenic horizon of soils, Pb concentrations increased significantly ($p<0.05$) from the OL subhorizon to the OH subhorizon (Table 3). There are two maxima in the distribution of Co in the soil profile — in the organogenic (OH subhorizon) and illuvial (B) horizons.

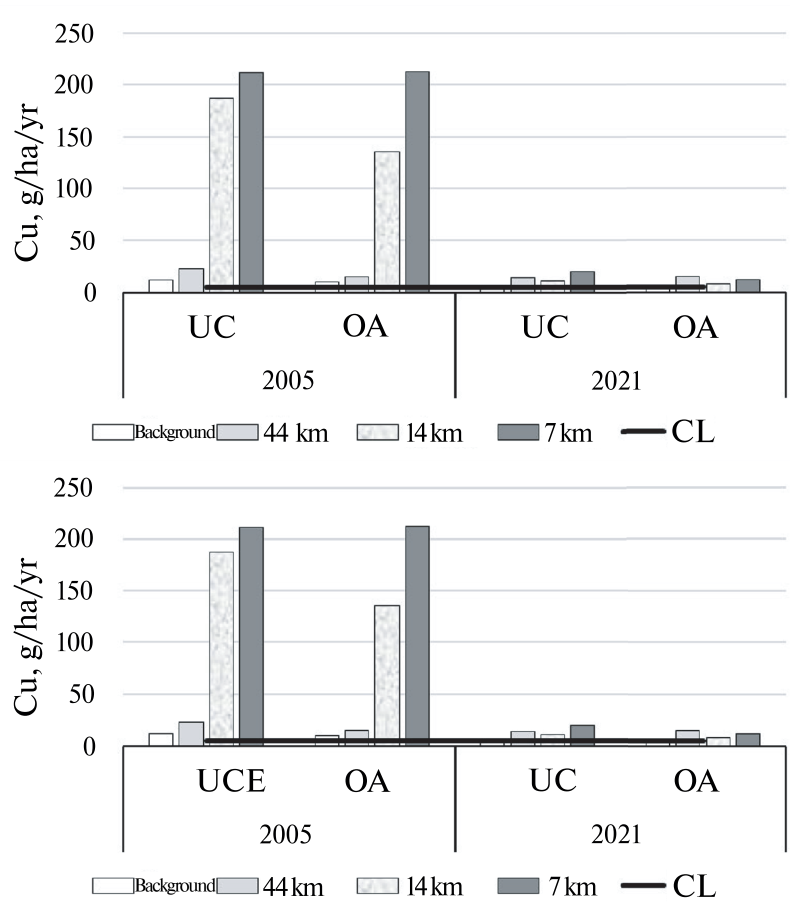

Fig. 2. Atmospheric deposition of nickel and copper during the period of the smelter active operation (2005) and in the period after its closure (2021).
Note. UFC — under forest canopy, OA — open area, CLL — critical load level (Reinds et al., 2006).

In the impact zone of the Pechenganickel smelter, at a distance of 44 km from the pollution source, the thickness of the organogenic horizon varied from 8 to 13 cm and corresponded to the natural variation. At a distance of 7 and 14 km from the plant, the range of variation in the thickness of the organogenic horizon was in the range of 5—9 cm, which is below the background values.

In sub-horizons OL, OF (44 km) and OL, OF, OH (7 km) there is an increase in pH value compared to the regional background, which confirms the idea of neutralization of acidity under conditions of pollution by acid-forming substances as a result of protonation of soluble and insoluble organic compounds and due to rapid cation exchange reactions (Sokolova et al., 1996; Acid precipitation..., 1999). Differences in the acidity of mineral horizons of background and disturbed forest biogeocenoses are not pronounced.

In 2021, at all PMP in the area of the smelter impact, a multiple increase of Ni, Cu, Co concentrations in both organogenic and mineral horizons compared to background values was revealed. In litter the content of most heavy metals is higher than in mineral horizons. The maximum accumulation of metals is observed at a distance of 7 km from the smelter: the excess of background values for Ni content in organogenic soil horizon reached 543—746 times, in mineral horizons — 225 (horizon E) and 14 (horizon B) times. Cu concentrations exceeded the background level in the organogenic horizon by 403—1075 times, in mineral horizons E and B — up to 73 and 7 times, respectively. The organogenic horizon showed higher accumulation of nickel compared to copper, which is associated with its significant predominance in the composition of emissions for several decades, up to 2015. Co concentration increased in the organogenic horizon — by 81—445 times, horizons E and B — by 33 and 4 times, respectively, relative to background values. A significant increase in sulfur content ($p < 0.05$) in the litter was detected only near the local source of pollution (7 km from the mill). The results of previous studies also showed that aerotechnogenic emissions are the main source of increased concentrations of Ni, Cu, Co and other heavy metals in the soil at a distance of 30—40 km from the plant. At the same time, the highest concentrations of heavy metals are noted near the local source of pollution at a distance of up to 10 km (Current..., 2008; Kola..., 2012; Dauwalter, Kashulin, 2018).

Table 3. Acidity and mobile forms of chemical elements (mg/kg) in the soil of pine forests at PMPs located at different distances from Pechenganickel smelter

Horizon	**thickness, cm**	**pH**	**Ni**	**Cu**	S	**Co**	**Cd**	**Pb**
Background area 275 km *								
OL	1.3 0.3	3.95 0.02	0.55 0.04	0.40 0.10	94 4	0.04 0.003	0.14 0.02	0.71 0.21
OF	4.0 1.3	3.88 0.07	0.74 0.10	0.38 0.07	101 8	0.11 0.014	0.22 0.03	4.32 0.41
OH	3.8 0.5	3.84 0.04	0.84 0.10	0.20 0.03	84 9	0.20 0.04	0.26 0.03	7.57 0.82
E	6.3 1.4	4.20 0.06	0.08 0.03	0.09 0.02	10 1	0.03 0.004	0.007 0.001	0.65 0.04
B	13.3 2.0	4.94 0.03	0.36 0.03	0.21 0.04	77 6	0.19 0.06	0.005 0.001	0.19 0.03
C	–	5.23 0.05	0.23 0.02	0.13 0.03	8 3	0.08 0.05	0.009 0.007	0.14 0.008
44 kilometers **								
OL	2.3 0.5	4.41 0.08	11.8 1.64	2.06 0.33	126 9	0.63 0.08	0.08 0.01	0.58 0.03
OF	4.2 0.7	4.16 0.07	19.1 2.35	2.56 0.54	140 15	1.14 0,12	0.15 0.02	2.49 0.68
OH	4.7 0.8	3.80 0.07	18.7 3.48	4.24 1.23	119 26	1.20 0.19	0.16 0.02	4.82 1.27
E	6.0 1.4	4.12 0.10	1.47 0.36	0.45 0.13	10 1	0.16 0.03	0.01 0.004	0.68 0.04
B	15.7 0.6	4.92 0.05	1.40 0.22	2.97 0.53	49 10	0.24 0.06	0.005 0.001	0.49 0.09
C		5.31 0.08	0.69 0.12	5.19 2.37	21 2	0.21 0.03	0.003 0.0002	0.37 0.05
14 kilometers **								
OL	1.4 0.5	4.07 0.05	135 13	41 9	131 6	4.60 0.37	0.25 0.03	2.83 0.25
OF	2.6 0.3	3.97 0.04	253 15	110 15	137 6	7.61 0.43	0.42 0.03	12.8 1.33
OH	2.5 0,2	3.89 0.04	205 7	78 13	133 12	6.97 0.34	0.47 0.03	13.9 1.18
E	6.2 0.9	4.17 0.07	4.03 0.99	1.97 0.49	5 1	0.16 0,02	0.008 0.002	0.68 0.07
B	13.0 0.5	4.95 0.09	3.91 1.15	0.53 0.19	77 7	0.67 0.11	0.008 0.002	0.49 0.05
C	–	5.38 0.07	1.06 0.19	0.34 0.13	28 3	0.74 0.16	0.004 0.001	0.30 0.01
7 kilometers **								
OL	2.0 0.4	4.34 0.05	410 33	161 24	173 11	17.8 1.48	0.37 0.04	5.29 0.62
OF	3.5 0.5	4.34 0,05	539 27	250 31	168 6	20.31 0.57	0.46 0.03	10.1 0.66
OH	3.0 0,3	4.29 0.05	456 30	215 28	150 6	16.23 1.295	0.54 0.07	12.9 1.34
E	3.7 0.2	4.44 0.07	18 3.4	6.98 1.32	15 3	0.995 0.17	0.02 0.005	0.53 0.05
B	14.2 1.2	4.90 0.04	5.06 0.87	1.56 0.23	45 10	0,80 0.20	0.008 0.002	0.39 0,05
C	–	5.23 0.07	3.14 0.60	1.11 0.38	23 11	0.76 0.18	0.006 0.002	0,44 0.09

Note. * — 2019 data, ** — 2021 data.

At 44 km from the smelter, a reliable ($p < 0.05$) increase of Pb concentration in illuvial horizon and soil-forming rock in 2.6 times compared to background values was revealed, in 7 and 14 km in organogenic horizons — in 1.7—7.5 times, in illuvial horizon (horizon B) — in 2.1—2.6 times. Concentrations of Cd at 7 and 14 km in organogenic and illuvial horizons are 1.6—2.6 times higher than background values. In the eluvial horizon (E horizon) Pb concentrations are comparable to the regional background.

The study of multi-year dynamics of Cu, Ni (for the period 2004—2021), Co, Cd, Pb content (for the period 2011—2021) showed that at the PMP, located 44 km from the pollution source, the content of heavy metals in the organogenic horizon of soils decreases ($p<0.05$) (Fig. 3). During this time, there was a significant ($p<0.05$) decrease in soil concentrations of Cu, Co, Pb at 7 and 14 km distance. Ni and Cd concentrations remained high in the soil. In 2021, there was an increase in Ni (7 and 14 km) and Cd (14 km) compared to the previous study period (2004). Over the study

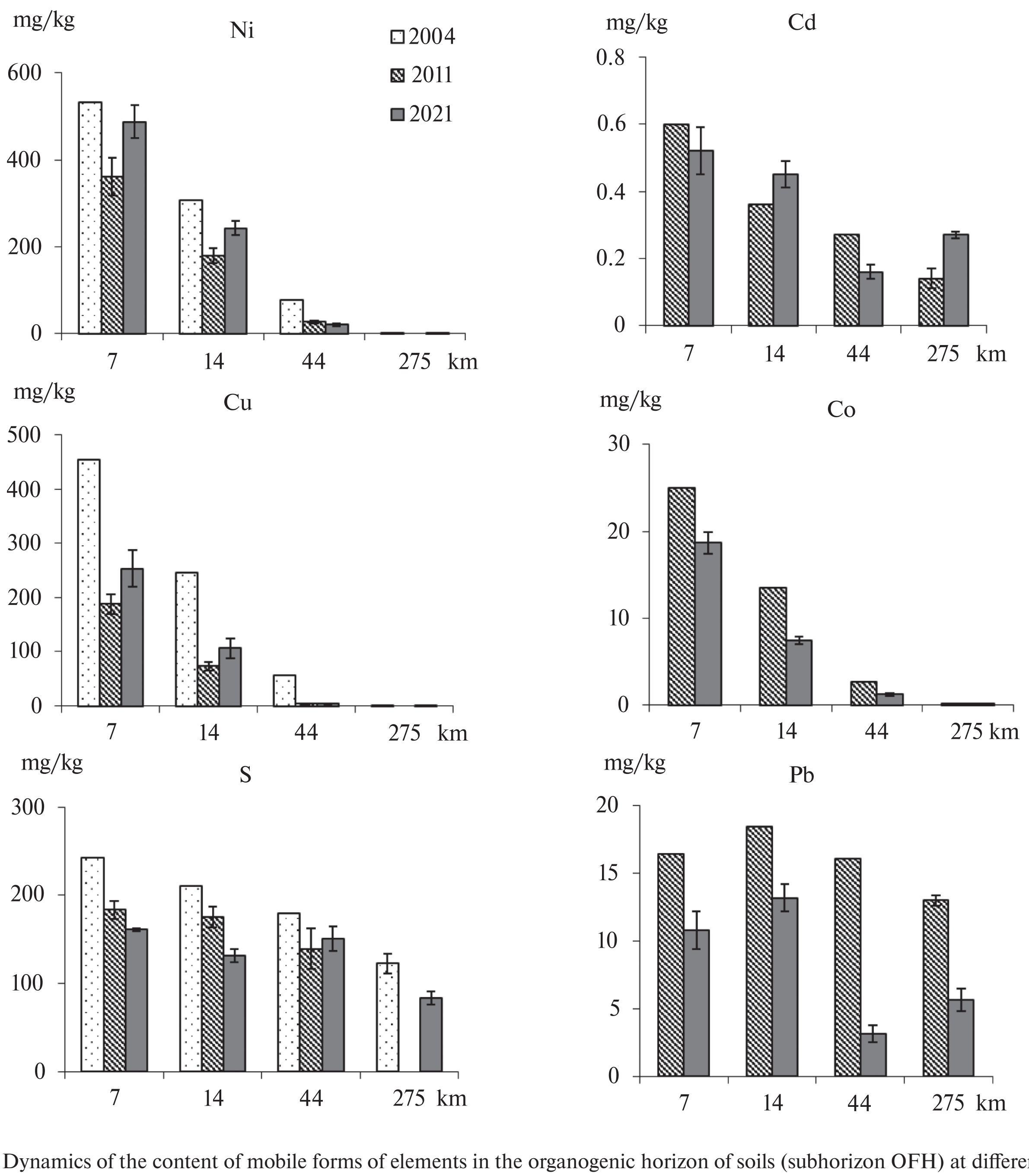

Fig. 3. Dynamics of the content of mobile forms of elements in the organogenic horizon of soils (subhorizon OFH) at different distances from the Pechenganickel smelter.
Note. Here and in Fig. 4. error bars are standard error.

period, S concentrations in soil decreased at all PMPs due to a sharp decrease in SO_2 inputs to the atmosphere.

The results of our studies demonstrate that, despite the reduction of heavy metals in soils, their concentrations remain significantly higher than background values. It is known that the possibilities of full self-purification from heavy metals are very limited and under the condition of cessation of input into ecosystems from anthropogenic sources the period of soil recovery is estimated in hundreds of years (Yakhnin et al., 1997; De Vries, Banker, 1996). This is due to the high degree of fixation of heavy metals in organogenic horizon and low rate of leaching into mineral horizons (Dynamics..., 2009).

Long-term studies on stationary sample plots in the area of impact of the Sredneuralsky smelter also indicate the absence of pronounced metal removal from soil in the context of a small time interval of 20 years (Vorobeychik, Kaigorodova, 2017). In our case, the comparison of the dynamics of priority pollutants in the composition of emissions among heavy metals (nickel and copper) showed that during the study period in the soil at the local source of pollution the concentrations of copper decreased, and nickel — even increased. This may be due to the fact that nickel was the predominant component of atmospheric emissions for a long period of active operation of Pechenganickel smelter and was accumulated to a greater extent in forest ecosystems (soil, phytomass).

Pine (Pinus sylvestris L.). Information on the content of heavy metals in photosynthetic organs has high indicative value for assessing negative impacts on ecosystems and is used to monitor the condition of forests in industrialized developed regions (Koptsik et al., 2016; Shergina et al., 2018). Under conditions of atmospheric pollution, pollutants enter the plant through root and foliar uptake, with soil being the most important source of heavy metals.

According to 1991—2019 data, background Ni content in pine needles varies from 0.3 to 3.3, Cu — from 1.8 to 4.4, Co — from 0.02 to 0.12, Cd — from 0.02 to 0.07, Pb — from 0.01 to 0.14 mg/kg. Maximum concentrations of Ni and Cu were observed in current year needles, Co and Pb — in perennial conifers. S concentrations in pine needles of the background area vary from 408 to 1040 mg/kg.

According to the data of 2019, the excess of background concentrations of Ni, Cu, Co, Pb ($p<0.05$) in pine needles was observed at all PMPs in the impact zone of Pechenganickel smelter (Table 4, Fig. 4). The violation of natural regularities of Ni and Cu distribution by age classes of needles was revealed. Near the source of pollution (7 km from the smelter), the maximum accumulation of Ni and Cu was observed in annual and perennial needles ($p<0.05$). The Ni content here exceeds the background values in the current year needles by 12—16 times, in annual and perennial needles by 58—76 times, Cu content by 2—4 times and 13—19 times, respectively. No reliable changes in nickel and copper concentration in needles depending on their age were found at the PMP located 44 km away from the smelter. However, here, an increase in the concentration of Ni — 6—14 times, Cu — 2—4 times compared to background values was also observed. Under aerotechnogenic impact in assimilating organs of pine trees, the age-specific distribution of Co and Pb, the concentrations of which are higher in perennial needles ($p<0.05$), is preserved. Under pollution conditions, Co content

Table 4. Heavy metals and sulphur content in pine needles at PMPs located at different distances from Pechenganickel smelter according to 2019 data, mg/kg.

PMP	Ni	Cu	Co	Cd	Pb	S
	Current year's needles					
275 km (background).	2.5 / 0.2	3.7 / 0.3	0.04 / 0.01	0.03 / 0.006	0.02 / 0.004	756 / 25
44 kilometers	15 / 1	7 / 1	0.35 / 0.04	0.006 / 0.001	0.05 / 0.006	1066 / 215
14 kilometers	41 / 3	14 / 2	1.29 / 0.14	0.01 / 0.003	0.14 / 0.02	1293 / 74
7 kilometers	25 / 2	9 / 1	0.41 / 0.05	0.04 / 0.009	0.10 / 0.02	1180 / 113
	Perennial needles (4—6 yrs).					
275 km (background).	1.1 / 0.2	2.4 / 0.1	0.07 / 0.01	0.04 / 0.01	0.11 / 0.01	668 / 47
44 kilometers	15 / 1	9 / 1	0.55 / 0.03	0.009 / 0.002	0.28 / 0.02	654 / 67
14 kilometers	72 / 4	31 / 2	2.63 / 0.27	0.013 / 0.003	0.79 / 0.08	959 / 30
7 kilometers	82 / 6	43 / 4	2.53 / 0.24	0.05 / 0.01	1.13 / 0.27	788 / 38

in pine needles increases 8—40 times compared background values, Pb — 2—20 times. Cd concentrations in pine needles (44 and 14 km from the smelter) either do not exceed the regional background values or are comparable (7 km) to the background. Sulfur content in pine needles at PMPs in the area affected by the smelter varies in a wider range than in background conditions, from 678 to 1839 mg/kg. A significant increase in S concentrations ($p<0.05$) in conifers of all age classes was detected at PMPs located 7 and 14 km from the source. Similar patterns of changes in sulfur content were revealed in spruce needles during the reduction of atmospheric emissions of SO_2 in the impact zone of the Severonickel smelter (Koptsik et al., 2016), which may reflect the needs of photosynthetic plant organs in this nutritional element.

During the study period, a decrease in Ni concentration from 26—29 (1991) to 13—15 mg/kg (2019), Pb — from 1.5—1.6 (2004) to 0.3—0.6 mg/kg (2019), Cd — from 0.02—0.05 (2004) to 0.006—0.011 (2019) mg/kg (Fig. 4) was detected in pine needles at the PMP44 km from the smelter.

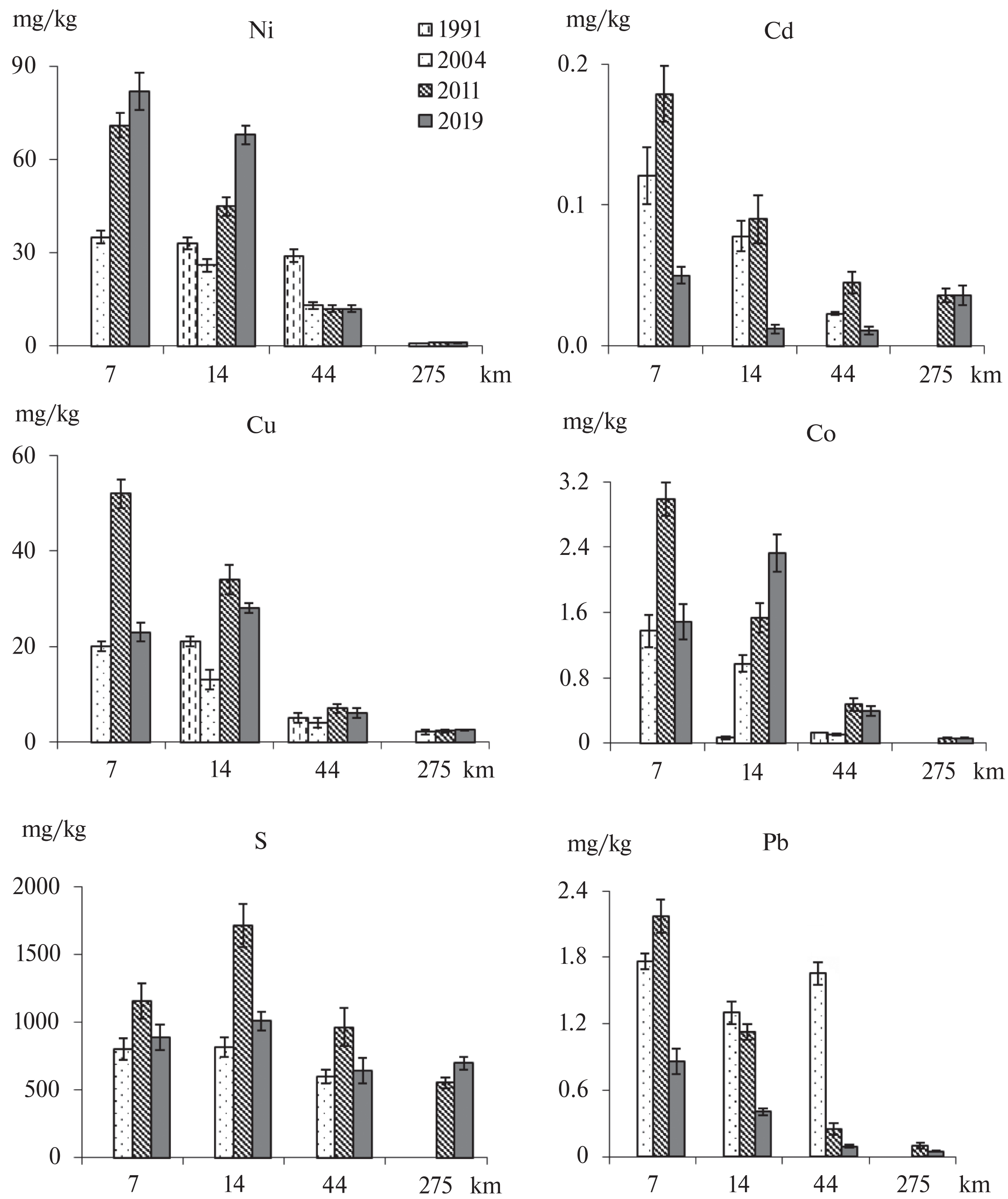

Fig. 4. Dynamics of heavy metals and sulfur content in annual pine needles at different distances from Pechenganickel smelter (1991—2019).

In 2019, Cu concentrations in pine needles decreased relative to the previous study period (2011), but either remained at or even exceeded the 1991 and 2004 values. Concentrations of Co in needles increased at more distant from the smelter PMPs (14 and 44 km), while near the pollution source (7 km) decreased to the values recorded in 2004 (Fig. 4).

At the PMPs located near the local source, at a distance of 7 and 14 km from the smelter, a reliable decrease in the content of Cd and Pb in the needles ($p < 0.05$), an increase — Ni ($p < 0.05$) was observed (Fig. 4). The results of other researchers (Koptsik et al., 2016) also indicate an insufficiently rapid decrease in nickel concentrations in assimilating organs, their changes are not always consistent with the positive dynamics of emission reduction. This may be due to the ability of nickel, compared to other heavy metals, to move more intensively from roots to aboveground organs (Kozlov, Barcan, 2000; Dynamics..., 2009) and the high level of accumulation of this element in soils near the Pechenganickel smelter. In addition, the pollutant content of pine needles was studied only during the period of the smelter active activity (until 2019).

In general, the results of this work confirm the regularities of heavy metal content increase in the soil-vegetation cover when approaching the pollution source and preservation of elevated heavy metals concentrations in conditions of technogenic load reduction, which were observed around other large industrial centers of copper-nickel production — Severonickel smelter (Monchegorsk, Murmansk Region) and Sredneuralsky smelter (Revda, Sverdlovsk Region) (Dynamics..., 2009; Koptsik et al, 2016; Vorobeychik, Kaigorodova, 2017; Sukhareva et al., 2020). In the work of E. L. Vorobeichik, S. Y. Kaigorodova (2017) showed the absence of expressed metal removal from the polluted area during the period of reduction of atmospheric emissions, which is considered by the authors as one of the mechanisms of long-term "conservation" of the biota of the impacted region in an oppressed state and indicates the low elasticity of ecosystems in relation to industrial pollution by heavy metals. A similar picture is observed in the permanent monitoring plots in the area of Pechenganickel smelter, where a significant excess of heavy metals relative to regional background values is preserved.

CONCLUSION

Forest biogeocenoses in the impact zone of the Pechenganickel Copper and Nickel smelter are exposed to significant technogenic load, as evidenced by numerous studies and the results of this work. When approaching the source of pollution, exceedance of background concentrations of the main pollutants — heavy metals (Cu, Ni, Cd, Co, Pb) and sulfur compounds in various components of forest biogeocenoses (atmospheric precipitation, soil, needles) was revealed.

For the first time the chemical composition of atmospheric precipitation and soil in the impact zone of Pechenganickel smelter in connection with the closure of the smelting shop of the smelter under conditions of almost complete cessation of emissions into the atmosphere was assessed. When comparing the period of closure of Pechenganickel smelter with the period of its active operation, there was a significant decrease in the concentrations of Ni, Cu, Co, Pb and Cd in atmospheric precipitation, Co, Pb — in soil, but the Ni content soil remains high. It is the composition of atmospheric precipitation that demonstrated the reduction of anthropogenic load on forest ecosystems in response to the reduction of pollutant input with aerotechnogenic emissions. However, in the soil cover of northern taiga forests the process of forest litter pollution continues, as evidenced by the increase in the concentration of nickel, which is one of the priority pollutants and has been accumulated for a long time not only in the soil, but also in the stand and ground cover plants. In this regard, the process of restoration of northern taiga forests formed in harsh natural and climatic conditions will require a long period of rehabilitation, especially in the vicinity of local sources of pollution

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REFERENCES

1. Chernen'kova T.V., Bochkarev Yu.N., Fridrikh M., Bettger T., The impact of natural and anthropogenic factors on radial tree growth on the northern Kola Peninsula, *Contemporary Problems of Ecology*, 2014, Vol. 7, No. 7, pp. 759—769.
DOI: 10.1134/S199542551407004X.
2. *Critical loads for sulphur and nitrogen. Report from Skokloster Workshop Skokloster*, Sweden, Skokloster, 1988, available at: https://doi.org/10.1007/978-94-009-4003-1_11 (May 04, 2023).
3. *Current state of terrestrial ecosystems in the joint Norwegian, Russian and Finish Border Area in Northern Fennoscandia*, Helsinki: Finish Forest Research Institute, 2008, 98 p.
4. Dauval'ter V.A., Kashulin N.A., Akkumulyatsiya i migratsiya khimicheskikh elementov v arkticheskikh nazemnykh i vodnykh ekosistemakh v zone vliyaniya vybrosov kombinata "Pechenganikel'" (Accumulation and migration of chemical elements in Arctic terrestrial and aquatic ecosystems in the zone of influence of emissions from the Pechenganikel smelter), *Trudy Karel'skogo nauchnogo tsentra RAN*, 2018, No. 3, pp. 31—42.
5. De Vries W., Banker D.J., Manual for calculating critical load of heavy metals for soils and surface water, *Report of DLO Winland Staring Centre*, Wageningen (The Neterlands), 1996, No. 114, 133 p.
6. De Vries W., Dobbertin M.H., Solberg S., van Dobben H.F., Schaub M., Impacts of acid deposition, ozone

exposure and weather condition on forest ecosystem in Europe: an overview, Plant and Soil. 2014. Vol. 380. No. 1—2. pp. 1—45. available at: https://doi.org/10.1007/s11104-014-2056-2 (May 04, 2023).

7. *Dinamika lesnykh soobshchestv Severo-Zapada Rossii* (Dynamics of forest communities in North-western Russia), Saint Petersburg: Izd-vo BIN RAN, 2009, 275 p.

8. Ershov V.V., Lukina N.V., Danilova M.A. et al., Assessment of the composition of rain deposition in coniferous forests at the northern tree line subject to air pollution, *Russian Journal of Ecology*, 2020, No. 4, pp. 319–328. DOI: 10.1134/S1067413620040050.

9. Evdokimova G.A., Mozgova N.P., Korneikova M.V., The content and toxicity of heavy metals in soils affected by aerial emissions from the Pechenganikel plant, *Eurasian Soil Science*, 2014, Vol. 47, No. 5, pp. 504—510.

10. Fedorets N.G., Bakhmet O.N., Medvedeva M.V. et al., *Tyazhelye metally v pochvakh Karelii* (Heavy metals in soils of Karelia), Petrozavodsk: Karel'skii nauchnyi tsentr RAN, 2015, 222 p.

11. *Godovoi otchet PAO "GMK "Noril'skii nikel'" za 2021 god* (Annual report of PJSC MMC Norilsk Nickel for 2021), available at: https://www.nornickel.ru/upload/iblock/53b/k7mqjhb1n9o0y8eieu0adzgn3b98z8xg/NN_AR_2021_Book_RUS_26.09.22.pdf (May 04, 2023).

12. Hale B., Robertson P., Plant community and litter composition in temperate deciduous woodlots along two field gradients of soil Ni, Cu and Co concentrations, *Environmental Pollution*, 2016, Vol. 212, pp. 41–47, available at: https://doi.org/10.1016/j.envpol.2016.01.032 (May 04, 2023).

13. Isaeva L.G., Sukhareva T.A., Otsenka sostoyaniya zelenykh nasazhdenii v zone vozdeistviya kombinata "Pechenganikel'" (Murmanskaya oblast') (Assessment of the green spaces' state in the impact zone of the Pechenganikel smelter, the Murmansk region), *Vestnik MGTU*, 2021, Vol. 24, No. 1, pp. 97—106.

14. Kashulina G., Caritat P., Reimann C., Snow and rain chemistry around the "Severonikel" industrial complex, NW Russia: Current status and retrospective analysis, *Atmospheric Environment*, 2014, Vol. 89, pp. 672–682. available at: https://doi.org/10.1016/j.atmosenv.2014.03.008 (May 04, 2023).

15. *Kislotnye osadki i lesnye pochvy* (Acid precipitation and forest soils), Apatity: KNTs RAN, 1999, 320 p.

16. *Kol'skaya gorno-metallurgicheskaya kompaniya (promyshlennye ploshchadki "Nikel"' i "Zapolyarnyi"): vliyanie na nazemnye ekosistemy* (Kola Mining and Metallurgical Company (industrial sites "Nickel" and "Zapolyarny"): impact on terrestrial ecosystems), Ryazan: Golos gubernii, 2012, 92 p.

17. Koptsik G.N., Koptsik S.V., Smirnova I.E., Kudryavtseva A.D., Turbabina K.A., Reaktsiya lesnykh ekosistem na sokrashchenie atmosfernykh promyshlennykh vybrosov v Kol'skoi Subarktike (The response of forest ecosystems to reduction in industrial atmospheric emission in the Kola Subarctic), *Zhurnal obshchei biologii*, 2016, Vol. 77, No. 2, pp. 145—163.

18. Koptsik G.N., Lukina N.V., Smirnova I.E., The effect of industrial aerial pollution on the composition of soil solutions in podzols, *Eurasian Soil Science*, 2007, No. 2, pp. 203–214.

19. Koptsik G.N., Ustoichivost' lesnykh pochv k atmosfernomu zagryazneniyu (Resistance of forest soils to air pollution), *Lesovedenie*, 2004, No. 4, pp. 61—71.

20. Korhola A., Weckstrom J., Nyman M., Predicting the long-term acidification trends in small subarctic lakes using diatoms, *Journal of Applied Ecology*, 1999, No. 36, pp. 1021–1034.

21. Kowalska A., Astel A., Boczoń A., Polkowska Ż., Atmospheric deposition in coniferous and deciduous tree stands in Poland, *Atmospheric Environment*, 2016, Vol. 133, pp. 145–155, available at: https://doi.org/10.1016/j.atmosenv.2016.03.033 (May 04, 2023).

22. Kozlov M.V., Barcan V.S., Environmental contamination in the central part of Kola Peninsula: history, documentation and perception, *Ambio*, 2000, Vol. 29, No. 8, pp. 512—517.

23. Lukina N.V., Nikonov V.V., *Biogeokhimicheskie tsikly v lesakh Severa v usloviyakh aerotekhnogennogo zagryazneniya* (Biogeochemical cycles in the Northern forests subjected to air pollution), Apatity: Izd-vo KNTs RAN, 1996, Part 1, 216 p.

24. Lukina N.V., Nikonov V.V., Pogloshchenie aerotekhnogennykh zagryaznitelei rasteniyami sosnyakov na severo-zapade Kol'skogo poluostrova (Absorption of aerotechnogenic pollutants by pine forest plants in the northwest of the Kola Peninsula)), *Lesovedenie*, 1993, No. 6, pp. 34—41.

25. Lyanguzova I.V., Gorshkov V.V., Bakkal I. Yu., Bondarenko M.S., Vozdeistvie pochvennogo zagryazneniya tyazhelymi metallami na napochvennyi pokrov sosnyaka lishainikovo-zelenomoshnogo v usloviyakh polevogo eksperimenta (Influence of soil pollution (heavy metals) on the lichen pine forest soil cover in conditions of field experiment), *Vestnik Povolzhskogo gosudarstvennogo tekhnologicheskogo universitet, Seriya: Les. Ekologiya. Prirodopol'zovanie*, 2015, No. 3 (27), pp. 74–86.

26. *Methods for Integrated Monitoring in the Nordic Countries*, Copenhagen: Nordic Council of Ministers, 1989, 280 p.

27. Mikhailova I.N., Dynamics of epiphytic lichen communities in the initial period after reduction of emissions from a copper smelter, *Russian Journal of Ecology*, 2020, Vol. 51, No. 1, pp. 38—45.

28. Reinds G.J., Groenenberg J.E., Vrieset W., *Critical Loads of copper, nickel, zinc, arsenic, chromium and selenium for terrestrial ecosystems at a European scale*, Wageningen: Alterra, 2006, 46 p.

29. Reinds G.J., Ilyin I., Groenenberg B.-J., Hettelingh J.-P., Critical and present loads of cadmium, lead and mercury and their exceedances, for Europe and Northern Asia, In: *Critical load, dynamic modelling and impact assessment in Europe: CCE Status Report*, Bilthoven: Coordination Centre for Effects, Netherlands Environmental Assessment Agency, 2008, pp. 91–101.

30. Shergina O.V., Mikhailova T.A., Kalugina O.V. Izmenenie biogeokhimicheskikh pokazatelei v sosnovykh lesakh pri tekhnogennom zagryaznenii (Change of biogeochemical indexes in pine forests under technogenic pollution), *Sibirskii lesnoi zhurnal*, 2018, No. 4, pp. 29–38.
DOI: 10.15372/SJFS20180404.

31. Sokolova T.A., Dronova T. Ya., Artyukhov D.B., Korobova N.L., Pakhomov A.P., Tolpeshta I.I., Polevoe modelirovanie pervykh stadii vzaimodeistviya kislykh osadkov s lesnymi podzolistymi pochvami (Field modeling of the first stages of interaction between acid precipitation and forest podzolic soils), *Pochvovedenie*, 1996, No. 7, pp. 847—856.
32. Sukhareva T.A., Ershov V.V., Isaeva L.G., Shkondin M.A. Otsenka sostoyaniya severotaezhnykh lesov v usloviyakh snizheniya promyshlennykh vybrosov kombinatom “Severonikel’” (Assessment of the state of the North taiga forests in terms of reducing industrial emissions by the Severonikel), *Tsvetnye metally*, 2020, No. 8, pp. 33—41.
33. *UNECE ICP Forests Programme Coordinating Centre: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests*, Eberswalde, Germany: Thünen Institute for Forests Ecosystems, 2020, available at: http://www.icp-forests.org/Manual.htm (September 27, 2024).
34. Vorobeichik E.L., Natural recovery of terrestrial ecosystems after the cessation of industrial pollution. 1. A state-of-the-art review, *Russian Journal of Ecology*, 2022, Vol. 53, No. 1, pp. 1—39.
35. Vorobeichik E.L., Kaigorodova S.Y., Long-term dynamics of heavy metals in the upper horizons of soils in the region of a copper smelter impacts during the period of reduced emission, *Eurasian Soil Science*, 2017, Vol. 50, No. 8, pp. 977—990.
36. Vorobeichik E.L., Trubina M.R., Khantemirova E.V., Bergman I.E., Long-term dynamic of forest vegetation after reduction of copper smelter emissions, *Russian Journal of Ecology*, 2014, Vol. 45, No. 6, pp. 498–507. DOI: 10.1134/S1067413614060150.
37. *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps*, Vienna, Austria: IUSS, 2022, 236 p.
38. Yakhnin E. Ya., Tomilina O.V., Delarov D.A., Atmosfernye vypadeniya tyazhelykh metallov i ikh vliyanie na ekologicheskoe sostoyanie pochv (Atmospheric emissions of heavy metals and their impact on the ecological state of soils), *Ekologicheskaya khimiya*, 1997, Vol. 6, No. 4, pp. 253—259.
39. Zakrzewska M., Klimek B., Trace element concentration in tree leaves and lichen collected along a metal pollution gradient near Olkusz (Soutern Poland), *Bulletin of Environmental Contamination and Toxicology*, 2018, Vol. 100, No. 2, pp. 245—249, available at: https://doi.org/10.1007/s00128-017-2219-y (May 04, 2023).

REFERENCE LIST

1. *Vorobeychik E. L.* Natural recovery of terrestrial ecosystems after cessation of industrial pollution. 1. Review of the current state of research // Ecology. 2022. No. 1, pp. 3—41.
2. *Vorobeychik E.L., Kaigorodova S.Yu.* Multiyear dynamics of heavy metal content in the upper soil horizons in the area of impact of the smelter during the period of reduction of its emissions // Soil Science. 2017. No. 8, pp. 1009—1024. DOI: 10.7868/S0032180X17080135
3. Annual Report of PJSC MMC Norilsk Nickel for 2021 [Electronic resource]. URL: https://www.nornickel.ru/upload/iblock/53b/k7mqjhb1n9o0y8eieu0adzgn-3b98z8xg/NN_AR_2021_Book_RUS_26.09.22.pdf (access date: 04.05.2023).
4. *Dauwalter V.A., Kashulin N.A.* Accumulation and migration of chemical elements in the Arctic terrestrial and aquatic ecosystems in the zone of influence of emissions from the Pechenganickel Combine // Proceedings of the Karelian Scientific Center of the Russian Academy of Sciences. 2018. No. 3, pp. 31—42.
5. Dynamics of forest communities of North-West Russia / Edited by V.T. Yarmishko. SPb.: VVM, 2009. 276 p.
6. *Evdokimova G.A., Mozgova N.P.,* Korneikova *M.V.* Content and toxicity of heavy metals in soils of the zone of impact of gas-air emissions from the Pechenganickel Combine // Soil Science. 2014. No. 5, pp. 625—631.
7. Acid precipitation and forest soils / Edited by V.V. Nikonov, G.N. Koptsik. Nikonov, G.N. Koptsik. Apatity: KSC RAS, 1999. 320 p.
8. *Isayeva L.G., Sukhareva T.A.* Assessment of the state of green plantations in the impact zone of the Pechenganickel Combine (Murmansk region) // Vestnik MSTU. 2021. Vol. 24, No. 1, pp. 97—106. DOI: 10.21443/1560-9278-2021-24-1-97-106
9. Kola Mining and Metallurgical Company (industrial sites “Nickel” and “Zapolyarny”): impact on terrestrial ecosystems / Edited by O.A. Khlebosolova. Ryazan: Golos Guberniya, 2012. 92 p.
10. *Koptsik G.N.* Stability of forest soils to atmospheric pollution // Forest Science. 2004. No. 4, pp. 61—71.
11. *Koptsik G.N., Koptsik S.V., Smirnova I.E., Kudryavtseva A.D., Turbabina K.A.* Response of forest ecosystems to the reduction of atmospheric industrial emissions in the Kola Subarctic // Journal of General Biology. 2016. Vol. 77, No. 2, pp. 145—163.
12. *Lukina N.V., Nikonov V.V.* Absorption of aerotechnogenic pollutants by plants of pine forests in the northwest of the Kola Peninsula // Lesovedenie. 1993. No. 6, pp. 34—41.
13. *Lukina N.V., Nikonov V.V.* Biogeochemical cycles in the forests of the North under conditions of aerotechnogenic pollution. Ч. 1. Apatity: KSC RAS, 1996. 216 p.
14. *Lyanguzova I.V., Gorshkov V.V., Bakkal I.Yu., Bondarenko M.S.* Impact of soil pollution by heavy metals on the ground cover of lichen-green-moss pine forest under field experiment // Bulletin of Volga Region State Technological University. Series: Forest. Ecology. Nature Management. 2015. No. 3 (27), pp. 74—86.
15. *Mikhailova I.N.* Dynamics of epiphytic lichen communities in the initial period after the reduction of smelter emissions // Ecology. 2020. No. 1, pp. 43—50. DOI: 10.31857/S0367059720010072
16. *Sokolova T.A., Dronova T.Y., Artyukhov D.B., Korobova N.L., Pakhomov A.P., Tolpeshta I.I.* Field modeling of the first stages of interaction of acidic precipitation

with forest podzolic soils // Soil Science. 1996. No. 7, pp. 847—856.

17. *Sukhareva T.A., Ershov V.V., Isaeva L.G., Shkondin M.A.* Assessment of the state of the northern taiga forests in the conditions of reducing industrial emissions by the Severonickel Combine // Nonferrous Metals. 2020. No. 8, pp. 33—41.
18. *Fedorets N.G., Bakhmet O.N., Medvedeva M.V., Akhmetova G.V., Novikov S.G., Tkachenko Y.N., Solodovnikov A.N.* Heavy metals in the soils of Karelia. Petrozavodsk: Karelian Scientific Center of RAS, 2015. 222 p.
19. *Shergina O.V., Mikhailova T.A., Kalugina O.V.* Changes in biogeochemical indicators in pine forests under anthropogenic pollution // Siberian Forestry Journal. 2018. No. 4, pp. 29—38. DOI: 10.15372/SJFS20180404
20. *Yakhnin E. Ya., Tomilina O.V., Delarov D.A.* Atmospheric deposition of heavy metals and their influence on the ecological state of soils // Ecological Chemistry. 1997. Vol. 6, No. 4, pp. 253—259.
21. *Chernen'kova T.V., Bochkarev Yu.N., Fridrikh M., Bettger T.* The impact of natural and anthropogenic factors on radial tree growth on the northern Kola Peninsula // Contemporary Problems of Ecology. 2014. Vol. 7, No. 7, pp. 759—769. DOI: 10.1134/S199542551407004X
22. Critical loads for sulphur and nitrogen. Report from Skokloster Workshop Skokloster [Electronic resource] // Sweden, Skokloster, 1988. URL: https://doi.org/10.1007/978-94-009-4003-1_11 (date of reference: 04.05.2023).
23. Current state of terrestrial ecosystems in the joint Norwegian, Russian and Finish Border Area in Northern Fennoscandia. Helsinki: Finish Forest Research Institute, 2008. 98 p.
24. *De Vries W., Banker D.J.*. Manual for calculating critical loads of heavy metals for soils and surface water // Report of DLO Winland Staring Center, Wageningen (The Neterlands). 1996. No. 114. 133 p.
25. *De Vries W., Dobbertin M.H., Solberg S., van Dobben H.F., Schaub M.*. Impacts of acid deposition, ozone exposure and weather condition on forest ecosystem in Europe: an overview [Electronic resource] // Plant and Soil. 2014. Vol. 380, No. 1—2, pp. 1—45. URL: https://doi.org/10.1007/s11104-014-2056-2 (date of reference: 04.05.2023).
26. *Ershov V.V., Lukina N.V., Danilova M.A., Isaeva L.G., Sukhareva T.A., Smirnov V.E.*. Assessment of the composition of rain deposition in coniferous forests at the northern tree line subject to air pollution // Russian Journal of Ecology. 2020. No 4, pp. 319—328. DOI: 10.1134/S1067413620040050
27. *Hale B., Robertson P.* Plant community and litter composition in temperate deciduous woodlots along two field gradients of soil Ni, Cu and Co concentrations [Electronic resource] // Environmental Pollution. 2016. Vol. 212, pp. 41—47. URL: https://doi.org/10.1016/j.envpol.2016.01.032 (date of reference: 04.05.2023).
28. *Kashulina G., Caritat P., Reimann C.* Snow and rain chemistry around the "Severonikel" industrial complex, NW Russia: Current status and retrospective analysis [Electronic resource] // Atmospheric Environment. 2014. Vol. 89, pp. 672—682. URL: https://doi.org/10.1016/j.atmosenv.2014.03.008 (date of reference: 04.05.2023).
29. *Koptsik G.N., Lukina N.V., Smirnova I.E.*. The effect of industrial aerial pollution on the composition of soil solutions in podzols // Eurasian Soil Science. 2007. No. 2, pp. 203—214.
30. *Korhola A., Weckstrom J., Nyman M.* Predicting the long-term acidification trends in small subarctic lakes using diatoms // Journal of Applied Ecology. 1999. No. 36, pp. 1021—1034.
31. *Kowalska A., Astel A., Boczoń A., Polkowska Ż.* Atmospheric deposition in coniferous and deciduous tree stands in Poland [Electronic resource] // Atmospheric Environment. 2016. Vol. 133, pp. 145—155. URL: https://doi.org/10.1016/j.atmosenv.2016.03.033 (date of reference: 04.05.2023).
32. *Kozlov M.V., Barcan V.S.* Environmental contamination in the central part of Kola Peninsula: history, documentation and perception //Ambio. 2000. Vol. 29, No. 8, pp. 512—517.
33. Methods for Integrated Monitoring in the Nordic Countries. Copenhagen: Nordic Council of Ministers, 1989. 280 p.
34. *Reinds G.J., Groenenberg J.E., Vrieset W.* Critical Loads of copper, nickel, zinc, arsenic, chromium and selenium for terrestrial ecosystems at a European scale. Wageningen, Alterra, 2006. 46 p.
35. *Reinds G.J., Ilyin I., Groenenberg B.-J., Hettelingh J.-P.* Critical and present loads of cadmium, lead and mercury and their exceedances, for Europe and Northern Asia / Eds. J-P. Hettelingh, M. Posch, J. Slootweg. Critical loads, dynamic modeling and impact assessment in Europe: CCE Status Report. Bilthoven: Coordination Center for Effects, Netherlands Environmental Assessment Agency, 2008. pp. 91—101.
36. *Vorobeichik E.L., Trubina M.R., Khantemirova E.V., Bergman I.E.*. Long-term dynamics of forest vegetation after reduction of copper smelter emissions // Russian Journal of Ecology. 2014. Vol. 45, No. 6, pp. 498—507. DOI: 10.1134/S1067413614060150
37. UNECE ICP Forests Programme Coordinating Centre: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests [Electronic resource] // Thünen Institute for Forests Ecosystems. Eberswalde, Germany, 2020. URL: http://www.icp-forests.org/Manual.htm (date of reference: 27.09.2024).
38. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. Vienna, Austria: IUSS, 2022. 236 p.
39. *Zakrzewska M., Klimek B.* Trace element concentration in tree leaves and lichen collected along a metal pollution gradient near Olkusz (Soutern Poland) [Electronic resource] // Bulletin of Environmental Contamination and Toxicology. 2018. Vol. 100, No. 2, pp. 245—249. URL: https://doi.org/10.1007/s00128-017-2219-y (accessed on 04.05.2023).