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Reaction of the Lichen *Hypogymnia physodes* to Dust Pollution in the Influence Zone of the Middle Timan Bauxite Mine

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Abstract—Here we present the results of long-term monitoring (2002–2017) of epiphytic lichen *Hypogymnia physodes* in the zone of influence of the Middle Timan bauxite mine (MTBM) (Komi Republic). Dust with a predominance of Al and Fe is the main environmental pollutant in this area. Three periods of the response of lichen to dust pollution are identified: shock, maximum changes, and adaptation. The dust pollution significantly reduced the projective cover of the species under study, increased the frequency of thallus necrosis, and decreased thallus linear dimensions. In the 10 years after we started our monitoring studies, the parameters of the vital state of *H. physodes* began to stabilize and then improve due to the adaptation of the lichen to chronic environmental pollution with dust. The study of changes in the content of main pollutants showed that, during the mining operation, they accumulate in the thalli of the lichen *H. physodes* in the following order: Al > Fe > Ni > Cu > Pb.

Keywords: epiphytic lichens, Middle Timan, bauxite mine, pollution, monitoring

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Bioindication methods are widely used when monitoring the state of ecosystems in the zones of technogenic impact. Epiphytic lichens are traditional indicators of pollution due to their increased sensitivity to changes in environmental factors (Mikhailova and Vorobeychik, 1995; Loppi et al., 1995; Dorozhkina et al., 1997; Byazrov, 2002; Krasnogorskaya et al., 2004; Paoli et al., 2012). Epiphytes are characterized by a higher rate of pollutant uptake and are less resistant to pollutants when compared with lichens of other ecological-substrate groups (Westman, 1975; Piervittori et al., 1997; van Dobben and Braak, 1999). The penetration of substances into the thalli of epiphytic lichens almost completely depends on the amount of precipitation and the composition of atmospheric air (Garty, 2001; Conti et al., 2004; Białońska and Dayan, 2005; Klos et al., 2007; Balabanova et al., 2014; etc.).

It has been established that the following characteristics of epiphytic lichen cover change in the areas of industrial pollution: species diversity decreases; sensitive species disappear and pollutant-resistant species are introduced; and the total projective cover, projective cover, and occurrence of many sensitive species and morphological and functional parameters of the vitality of thalli decrease (Trass, 1985; Gorshkov, 1991; Bargagli and Barghigiani, 1991; Perkins, 1992; Mikhailova and Vorobeitchik, 1995; Byazrov, 2002; Józwiak and Józwiak, 2009; Golovko et al., 2018).

In Russia, the Middle Timan bauxite mine (MTBM), located in the northern part of the Knyazhpogostsky district of the Komi Republic, is one of the largest industrial enterprises. The mining enterprise AO Timan Bauxite has been carrying out operational work at the MTBM since 1998. The Vorykva group of deposits is being mined (Vezhayu-Vorykvinskoye, Verkhne-Shchugorskoye, Vostochnoye, and Svetlinskoye). Aluminum oxides (48.69%) and iron oxides (27.87%) are the dominant components in the chemical composition of bauxites (Kotova and Vakhrushev, 2011). The quarry mining method at MTBM leads to the destruction of natural ecosystems and the pollution of vegetation, soils, and surface waters in areas adjacent to the industrial zone. Red bauxite dust is the main polluting ingredient, which is formed during the blasting, transportation, storage, processing, and loading of ore at the central charge warehouse. Fine fractions (Lee et al., 2017), which predominate in the granulometric composition of the bauxites of the Vezhayu-Vorykvinskoye deposit, are especially dangerous for natural ecosystems and human health (Kotova and Vakhrushev, 2011). Gaseous substances and solid particles formed during the operation of special equipment, automobile and railway transport, and dusting from the surface of overburden dumps and roadbeds are also pollutants. An excess of background contents of Al, Fe, Cu, Mn, Co, nitrites, ammonium ions, and nitrates, as well as, to a lesser extent, Si, Ni, Cr, Zn, Pb, Sr, Ti, etc., has been recorded in the composition of gas and dust emissions from the territory of the MTBM. The metal content near technological facilities is four or more times higher than background values (Afanasenko et al., 2010). According to the calculations of the maximum permissible discharge (MPD) standards, the projected quantity of emissions into the atmosphere received annually from the facilities of the Vezhayu-Vorykvinsky deposit has been determined: gross emissions of about 5511.6 t, including nitrogen oxides (636.34 t), carbon monoxide (1111.81 t), sulfur dioxide (786.04 t), and suspended solids (1405.0 t), including inorganic dust (1058.85 t) and soot (344.7 t).

Comprehensive monitoring studies of the state of the main components of natural landscapes, including lichens, were carried out in the territory of the MTBM (in the area of the Vezhayu-Vorykvinsky deposit development) in the period of 2002–2017. The epiphytic lichen *Hypogymnia physodes* (L.) Nyl, which is widespread in taiga forests, was chosen as a model. The species belongs to the class of medium-sensitive species to air pollution (Trass, 1985) and is often used as a bioindicator in the assessment of atmospheric pollution (Mikhailova and Vorobeychik, 1999; Poličnik et al., 2004; Białońska and Dayan, 2005; Mikhailova and Krzniasev, 2012; Koroleva and Revunkov, 2016; etc.).

The aim of the work was to study the response of the lichen *H. physodes* to pollution by dust emissions resulting from the bauxite mining. The main parameters for the assessment were the projective cover of tree trunks with lichen, the vital state of thalli, and the dynamics of accumulation of major pollutants (metals) in lichen samples.

It should be noted that the effect of dust pollution on lichens is less studied (Zvereva et al, 2008; Paoli et al., 2014; Rai, 2016; Degtjarenko et al., 2018) when compared with the effect of acid-forming gaseous emissions (SO_2, NO_x, NH_3, etc.), the most harmful for epiphytic lichens (Hawksworth and Rose, 1970; Skye, 1979; Nielson and Martin, 1982; Insarova, 1982; Santamaria and Martín, 1997; van Herk, 2001; Sujetoviene, 2015; etc.).

MATERIALS AND METHODS

The MTBM is located in the middle part of the Timansky Ridge in the northeast of the East European Plain. The territory is an elevated (to varying degrees dissected hollow–hilly–steeply sloping) plain with a predominance of absolute altitudes within 200–360 m above sea level. The climate is moderately continental with moderately harsh winters and cool short summers. The average annual air temperature is negative and is –2°C. The average amount of annual precipitation is 492 mm. During the year, south and southwesterly winds prevail (*Atlas*..., 2011).

According to the botanical and geographical zoning of the European part of Russia, the territory belongs to the Northern European taiga province, the district of spruce, spruce–pine, and spruce–larch forests of the Timan region (Isachenko and Lavrenko, 1980). The main types of vegetation are spruce green-mossy and long-mossy forests and raised bogs alternating with secondary spruce–birch forests (Lesa Respubliki Komi, 1999). Before the construction of the mine and mine-related infrastructure, the area was not very economically developed, so most of the territory was represented by undisturbed or slightly disturbed landscapes.

Monitoring of the lichen state was carried out in the summer (end of August) at four permanent monitoring plots (PMPs) with an area of 300 m^2 each. The PMPs were selected in 2002–2003 according to the ICP Forests methodology (ICP Forests manual, 1997). Each PMP is surrounded by at least a 10-m buffer zone. The plots are located on homogeneous drained sections of watersheds in old-age spruce forests of the green moss group of types at different distances from industrial facilities in three zones: strongly polluted (PMP 6), medium polluted (PMP 1, PMP 11), and conditionally background (PMP 15) zones (Fig. 1). The plots were selected taking into account the wind rose and the expected runoff of pollutants.

PMP 6 is a small preserved part of the spruce forest massif adjacent to the dump of the charge warehouse from the southeastern side. From the north and east it is bounded by an automobile access road and railway. During the initial monitoring period, the trees and shrubs at PMP 6 were covered with a layer of red bauxite dust. The other plots experienced less impact of the mine due to their greater distance from the objects of operation. PMP 1 (located 20 m north of the border of quarry 2) and PMP 11 (on the western border of quarry 1) were located in the zone of medium pollution. PMP 15, located 3.5 km north of quarry 2, was taken as the conditionally background one, which meets the requirements for the location of background plots. Territories located at a distance of at least 3 km from sources of pollution are considered background ones (Egoshina and Shikhova, 2008). It is important to note that, in 2003, PMP 15 was located 8.5 km from the site where the field development started (the area of PMP 1); with the development of the deposit, the boundary of the technogenic zone shifted.

The projective cover of the lichen *H. physodes* was evaluated on the trunks and branches of ten large trees of Siberian spruce (*Picea obovata* Ledeb.) at a height of up to 1.7 m within the PMP boundaries. The scale given in the work of M. Kauppi and P. Halonen (1992) is used: 7 = >50%, 6 = 26–50%, 5 = 11–25%, 4 = 3–10%, 3 = low cover: <3%, and 2 = few: there are a lot of thalli, but they do not form a real cover; 1 = very few: one or two thalli. To study the vitality of *H. physodes* thalli, 20–30 samples of lichen were taken annually on 10 trees in the buffer zone surrounding each PMP. The pathomorphological analysis of the

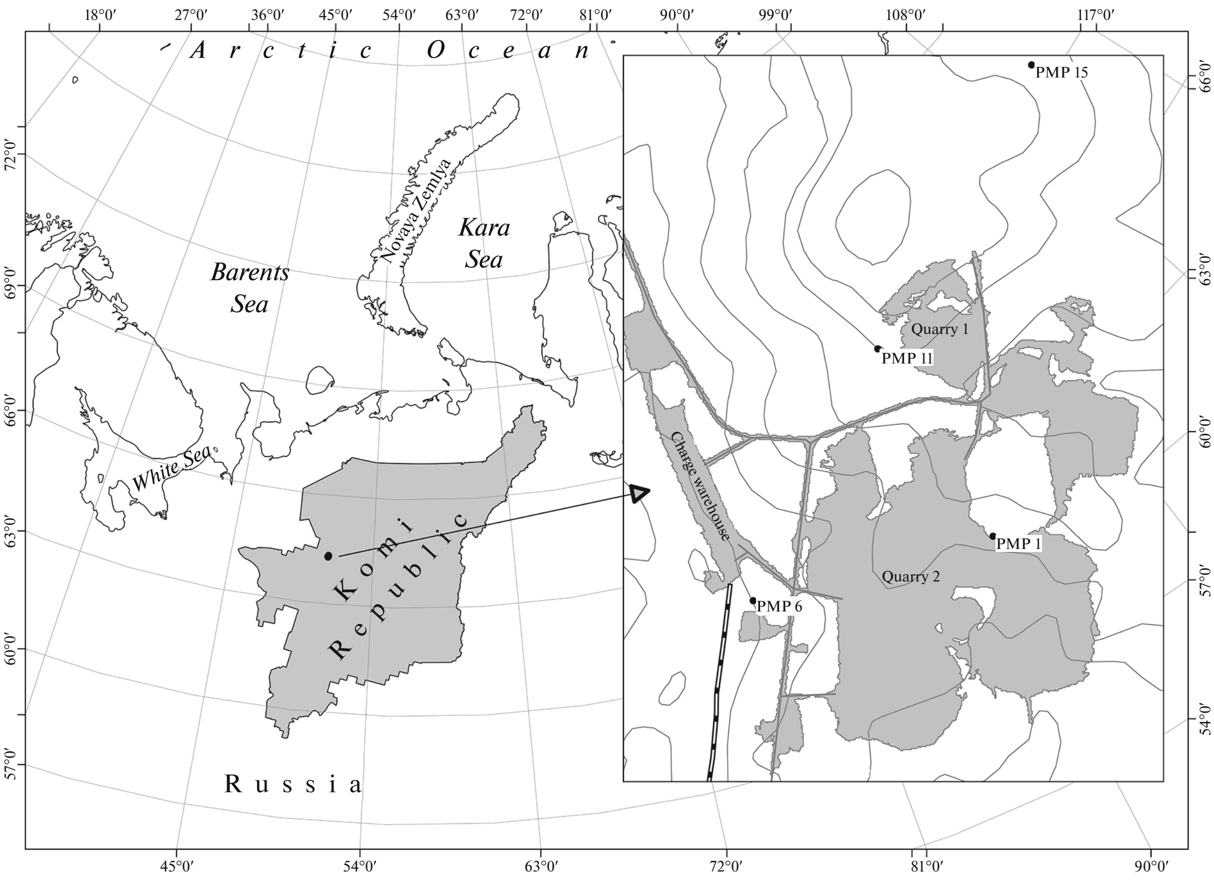

Fig. 1. Map of the survey region with permanent monitoring plots (PMP)

collected specimens was carried out according to the following traits: the size and shape of thalli, changes in the nature of the surface and typical coloration, the presence of chlorosis and necrosis and their localization, and infection with lichenicolous fungi. The necrotic area was measured using a measuring grid under a binocular microscope at 8 × 2 magnification. For further analysis, the averaged values of the projective cover of lichens on the tree trunks and the area of necrosis of thalli were used.

In the buffer zone, the samples of *H. physodes* were taken from spruce trunks and branches (on at least ten trees) at a height of 1.5–1.7 m to determine the content of pollutants. In the laboratory, the samples were cleaned from impurities, dried at room temperature, and ground using an electric grinder. The chemical analysis was carried out in the ecoanalytic laboratory of the Komi Institute of Biology, National Science Center, Ural Branch, Russian Academy of Sciences (certificate of accreditation ROSS RU.0001.511257 dated September 25, 2015). The content of acid-soluble forms of Al, Fe, Mn, Pb, Ni, Cu, and Zn was determined using inductively coupled plasma atomic emission spectrometry according to Federal Environmental Normative Documents (PND F 16.1:2.3:3.11-98). The analysis was performed on a Spectro Ciros CDD instrument (Germany).

Due to the lack of standards for the content of trace elements in lichens (Bettinelli et al., 1996), scales proposed by P.L. Nimis and R. Bargagli (1999) (cited according to Bargagli and Nimis, 2002), as well as data on the level of accumulation of heavy metals in background territories in the taiga zone of the Komi Republic, were used to interpret the values of the content of metals in lichen (Vasilevich, M.I. and Vasilevich, R.S., 2018).

Statistical data analysis was performed in the ExStatR program (Novakovsky, 2016). The cluster analysis dendrogram was constructed using the distance metric of one minus the Pearson correlation coefficient. Clustering was performed by the unweighted pair group method with arithmetic mean (UPGMA).

RESULTS

Vital State of Thalli of the Lichen Hypogymnia physodes

During the monitoring period, a significant deterioration in the state of *H. physodes* thalli was recorded at all PMPs, with the exception of the conditionally background one: chlorosis and necrosis of the central

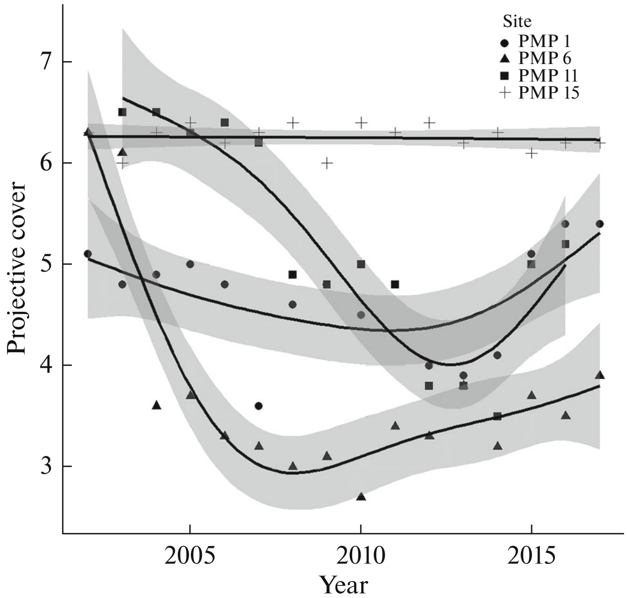

Fig. 2. Change in the projective covering of the lichen *Hypogymnia physodes* on *Picea obovata* trunks. The lines display regression dependencies obtained by the method of generalized additive models (GAMs) based on splines. The 95% confidence interval is in gray.

areas, the dying off of lobe ends, a change in the characteristics of the upper cortical layer (deviation from the typical color, the appearance of roughness, and cracking), and infection with lichenicolous fungi. In the case of severe chronic pollution, a decrease in the size of thalli, the formation of shortened and deformed lobes, development of lobules, and the suppression of vegetative reproduction were observed (Table 1).

At PMP 6, the vital state of lichen thalli deteriorated in the first year of monitoring, which is associated with dusting of forest massifs adjacent to the charge warehouse. The thalli had a reddish tint; their significant damage was observed, and dying off and dead old thalli were found on the lower spruce branches covered with bauxite dust.

Projective Cover of Thalli of the Hypogymnia physodes Lichen

A 7-point scale proposed by M. Kauppi and P. Halonen (1992) was used to assess the change in the projective cover of the lichen *H. physodes* on the trunks and branches of spruce. A decrease in the projective cover of lichen was recorded in all areas within the zone of exposure to MTBM emissions, especially strongly at PMP 6 (Fig. 2).

Metal Accumulation in Lichen Thalli

The dynamics of accumulation of the main pollutants (Al, Fe, Mn, Pb, Ni, Cu, and Zn) were studied (Afanasenko et al., 2010) in samples of the lichen *H. physodes* during monitoring studies.

The amount of lead in the initial monitoring period (2002–2006) varied from 7.4 ± 0.8 (PMP 15) to 8.7 ± 2.9 (PMP 1) mg/kg (Table 2), which was higher than the average content of the element in fruticose epiphytic lichens established for the background territories of the taiga zone of the Komi Republic, 2.83 0.76 mg/kg (Vasilevich, M.I. and Vasilevich, R.S., 2018).

According to Bargagli and Nimis (2002), the Pb content in lichens in natural background areas does not exceed 4 mg/kg. The highest amount of lead was recorded in the zone of heavy pollution (PMP 6); its content in the period 2012–2017 increased almost 2 times when compared to the initial one (Table 2).

In the period 2002–2006, the amount of copper and nickel in lichens at the background plot PMP 15 was approximately the same and slightly exceeded the average content of these elements in epiphytic lichens of the background areas in the Komi Republic (Cu, 2.49 ± 0.99 mg/kg, Ni, 1.60 ± 0.87 mg/kg) (Vasilevich, M.I. and Vasilevich, R.S., 2018). According to Bargagli and Nimis (2002), the content of Cu in lichens of natural ecosystems does not exceed 7 mg/kg and that of Ni does not exceed 5 mg/kg. During the survey period, the accumulation of these metals was recorded at all monitoring plots (with the exception of PMP 15 for Ni) (Table 2), which indicates the technogenic character of their release into the environment.

In the Komi Republic, the average zinc content in fruticose epiphytic lichens of the taiga zone is 43.7 ± 11.7 mg/kg; the maximum content is 90 mg/kg (Vasilevich and Vasilevich, 2018). According to the data of Bargagli and Nimis (2002), the amount of Zn in lichens at background plots does not exceed 30 mg/kg; areas are considered polluted beginning from 94 mg/kg. During the monitoring period at the MTBM, the Zn content in lichens at all plots, including the conditionally background one, was quite high (Table 2), which is apparently due to the geochemical features of the study area (Lodygin et al., 2018) and the accumulation of the element in lichen cells (Loppi, 2006). The increase in the zinc content was not recorded during the entire survey period.

The vegetation of the northern part of the taiga zone is characterized by a significant accumulation of iron and manganese from soil enriched with ferruginous minerals and accompanying manganese due to the peculiarities of the soil-forming process (Khrenov, 1996; Kirilyuk et al., 2004). The Mn content in *H. physodes* at all plots analyzed was initially high, from 365 ± 135 (PMP 1) to 608 ± 299 mg/kg (PMP 6) (Table 2); the maximum index (1 100 ± 300 mg/kg) was recorded at PMP 6 in 2008. However, the increase in the accumulation of the metal in polluted areas was not observed over the entire survey period. In the Komi Republic, the average Mn content in fruticose epiphytic lichens at the background plots is 246 ± 178.6 mg/kg,

Table 1. Pathomorphological traits of thalli of the lichen *Hypogymnia physodes*

PMP no.	Characteristics of *Hypogymnia physodes* thalli (percentage of necrosis, %) in years of monitoring				
	2002	2006	2010	2014	2017
PMP 6 Zone of strong pollution	Gray color, pinkish and brownish spots, dust coating. Roughness of the upper cortical layer, single dead old thalli, suppression of vegetative reproduction (10–12)	Reddish brown thick layer of dust. Decrease in thalli size. Severe roughness and ruptures of the upper cortical layer, necrosis at lobe ends and in central areas of the thalli, infection with lichenicolous fungi (<20 (25))	Like in 2006 (<40 (45))	Reddish brown thick layer of dust, growing ends of lobes are gray. Roughness and thickening of the upper cortical layer, die-off of lobe ends and central areas of old thalli, formation of lobules and papillae, formation of small compact thalli with shortened lobes (<30)	Reddish brown thick layer of dust. Small compact thalli prevail. Old thalli have narrow twisted lobes, necrosis is visible only at the lobe ends, which have a lighter color, in the central areas of thalli, due to the dust layer, damages are not visible (20–30)
PMP 1 Zone of medium pollution	Gray color. Roughness of the upper cortical layer (<5)	Gray color, a faint dusting (<10)	Gray color, faint dusting (>10). Decrease in thalli size. Roughness and thickening of the upper cortical layer, necrosis of lobe ends (<10)	Gray color, faint dusting. Roughness, thickening of the upper cortical layer, necrosis of lobe ends in old thalli; decrease in size, shortened lobes, suppression of vegetative reproduction in young thalli (<5)	Gray color, faint dusting. Decrease in thalli size. Roughness, chlorosis and necrosis (point) of the upper cortical layer, necrosis of lobe ends, shortened lobes, formation of lobules (<5)
PMP 11 Zone of medium pollution	Gray color. Slight roughness and darkening of the cortical layer in central areas, dead lobe ends (single) in old thalli (<1)*	Gray color. Roughness, darkening, chlorosis (spots) of the upper cortical layer, mass die-off of lobe ends (<10)	Gray color, faint dusting. Roughness and darkening of the cortical layer, necrosis of the central areas, development of lobules (15 (25))	Gray color, faint dusting. Decrease in thalli sizes. Rough upper cortical layer, die-off of lobe ends, necrosis of central areas of old thalli (<15)	Gray color, faint dusting. Decrease in thalli sizes. Strong roughness and ruptures of the upper cortical layer, necrosis of central areas of thalli and lobe ends, the appearance of malformed thalli, infection with lichenicolous fungi, suppression of vegetative reproduction (10–15)**
PMP 15 Conditional background	Gray color. Slight roughness and darkening of the cortical layer in central areas of old thalli, necrosis of lobe ends (single) (1–3)	Like in 2002 (1–3)	Like in 2002 (1–3)	Like in 2002 (1–3)	Like in 2002 (1–3)

* Data from 2003; ** data from 2016.

Table 2. Content of heavy metals (mg/kg) in thalli of the lichen *Hypogymnia physodes* in different monitoring periods (means ± standard deviation)

PMP no.	Period	Pb	Cu	Ni	Zn	Mn	Fe	Al
PMP 6	2002–2006	7.8 ± 5.6	7.6 ± 2.4	8.0 ± 4.5	104 ± 32.8	608 ± 299	3678 ± 3369	2951 ± 2634
	2007–2011	13.0 ± 2.6	12.0 ± 2.4*	12.8 ± 2.6	98.2 ± 16	796 ± 192	12620 ± 2678**	14200 ± 3834**
	2012–2017	14.2 ± 4.0	16.4 ± 2.3*	16.2 ± 4.0	78.8 ± 8.9	623 ± 110	18333 ± 4320*	20667 ± 3445*
PMP 1	2002–2006	8.7 ± 2.9	5.2 ± 1.3	5.5 ± 3.4	70.8 ± 20.7	365 ± 135	1755 ± 1517	1717 ± 1492
	2007–2011	8.0 ± 3.1	7.1 ± 1.1	5.5 ± 0.9	97.6 ± 19.4	464 ± 238	3660 ± 817	4640 ± 1552*
	2012–2017	6.2 ± 0.9	10.3 ± 2.6*	6.4 ± 1.8	79.3 ± 20.5	310 ± 124	4817 ± 977	5417 ± 857
PMP 11	2002–2006	8.4[1]	3.9[1]	1.2[1]	87[1]	810[1]	410[1]	367[1]
	2007–2011	6.9 ± 1.4	5.4 ± 0.6	4 ± 0.3	99.6 ± 14	540 ± 128	3320 ± 476	4900 ± 1332
	2012–2017	7.9 ± 3.1	8.5 ± 2.7	5.9 ± 1.9	95.6 ± 10	534 ± 225	5540 ± 2561	7020 ± 2275
PMP 15	2002–2006	7.4 ± 0.8	3.6 ± 0.5	3.6 ± 1.4	103 ± 22.7	422 ± 136	348 ± 92	279 ± 100
	2007–2011	6.0 ± 1.7	4.5 ± 0.8	2.0 ± 0.3	115 ± 31.6	570 ± 106	378 ± 61	434 ± 143
	2012–2017	3.9 ± 0.8	4.7 ± 0.5	1.6 ± 0.2	103 ± 19.4	597 ± 215	365 ± 92	438 ± 118

* Average value of the period differs from the previous one at significance level $p < 0.05$ (Student's *t*-test was used); ** average value of the period differs from the previous one at significance level $p < 0.01$. [1] The lack of data does not allow us to estimate the standard deviation.

the maximum content is 1100.0 mg/kg (Vasilevich, M.I. and Vasilevich, R.S., 2018). According to Bargagli and Nimis (2002), a Mn content above 140 mg/kg indicates a very high level of pollution.

Iron is an element for which a high and statistically significant increase in its amount in lichens was recorded (Table 2). At the beginning of monitoring, its content in the samples varied from 220 ± 60 (PMP 15) to 1800 ± 500 mg/kg (PMP 6). In recent years of monitoring, a particularly high amount of the element was recorded at PMP 6 (up to 25000 ± 7000 mg/kg in 2014). If in 2002 its content at PMP 6 exceeded background values (PMP 15) by 8 times, then in 2017 it was already 44 times higher. In the Komi Republic, the average Fe content in fruticose epiphytic lichens at background plots is 139.0 ± 76.7 mg/kg; the maximum content is 400 mg/kg (Vasilevich, M.I. and Vasilevich, R.S., 2018).

A similar pattern is found in the accumulation of aluminum. The area of the charge warehouse (PMP 6) is the most polluted one: the Al content in lichen thalli was 1150 ± 310 mg/kg in 2002 and 22000 ± 6000 mg/kg in 2017 (Table 2). The background area (PMP 15) remained the cleanest one, where the element content was 204 ± 54 mg/kg in 2002 and 650 ± 170 mg/kg in 2017. According to the content of aluminum, the difference between the background and the most polluted areas was almost 6 times in 2002 and 34 times in 2017. According to M.I. Vasilevich and R.S. Vasilevich (2018), in the taiga zone of the Komi Republic, the average Al content in fruticose epiphytic lichens of background areas was 139.6 ± 87.1 mg/kg; the maximum content was 450 mg/kg.

DISCUSSION

The abovementioned morphological modifications of thalli of the lichen *H. physodes* are due to the effect of pollution. Lichens are most vulnerable to dust falls in summer during the period of active photosynthesis and growth (Vainstein, 1984). The roughness and thickening of the upper cortical layer, the formation of compact thalli with shortened lobes are found in stressful situations to neutralize the effects of negative factors. The change in color to complete discoloration (chlorosis) is associated with the degradation of chloroplasts of the photobiont, and cracking and necrosis (the appearance of brown and black spots and areas up to the dying off of the thalli) are associated with the destruction of the mycobiont as well (Malysheva, 1995; Byazrov, 2002).

It was found that indicators of thalli vitality annually deteriorated at PMP 6 due to the high level of pollution that persisted throughout the entire monitoring period. In particular, a decrease in linear dimensions has been recorded since 2004 and infection with lichenicolous fungi since 2005. The development of lichenicolous fungi on thalli of *H. physodes* may be dependent on air pollution. Thus, according to the results of studies conducted in Spain (Glenn et al., 1997), the number of species of lichenicolous fungi significantly increased with increasing air pollution by solid particles, as well as the number of species of fungi adapted to pollution. The maximum deterioration of the vital state was observed in 2010, when the area of dead parts of thalli reached almost 40%. Since 2011, despite the dust layer covering the lichen thalli, the proportion of necrosis has gradually decreased and in recent years of observations did not exceed 30% (Table 1, Fig. 3). By that time, the population of *H. physodes* had significantly changed: small compact thalli with shortened lobes, a lumpy and thickened upper cortical layer, point necrosis on the surface of the thalli and the lobe ends began to prevail. A few older, larger thalli looked depressed, often with a browned, dying off central part, narrow and twisted lobes, on which outgrowths (papillae and lobules), atypical for this lichen, developed.

Pathomorphological changes in the thalli of *H. physodes* are not so pronounced at plots characterized by an average level of pollution (PMP 1 and PMP 11) (Table 1, Fig. 3). These plots are characterized by a similar response of lichen to an increase or decrease in emissions. Thus, PMP 1 was exposed to the strongest impact during the initial period of the operational work in the northern part of quarry 2, which caused a gradual increase in the necrosis area of lichen thalli in 2002–2006. Later, due to the relocation of work to other areas of the quarry, the intensity of dust falls at PMP 1 decreased and, accordingly, the indicators of the vital state stabilized (2007–2010) and, in recent years (2011–2017), even improved somewhat. Small thalli with shortened lobes, more resistant to pollution, began to form, which prevailed in the population by the end of surveys. No restoration of the characteristics of the epiphytic lichen cover to the initial values was observed, since the anthropogenic impact on the forest ecosystem persisted. Despite a significant decrease in the proportion of necrosis in recent years, various morphological abnormalities were recorded on the thalli.

A similar situation was observed at PMP 11 located on the western side of quarry 1. Deforestation directly on the border with the monitoring plot and the intensive development of bauxite deposits in the quarry in 2006–2009 led to a deterioration in the indicators of the vital state of lichens. After the termination of mining activity, the epiphytic lichen cover recovered very slowly: during the period from 2009 to 2017, the proportion of necrosis decreased only one and a half times. This is explained, first and foremost, by a change in the habitat, namely, the fall of trees both on the border with the quarry and at the monitoring plot. Since 2012, smaller thalli with shortened lobes have been found, but the formation of compact forms resistant to prolonged stress effects was not observed.

Morphological traits of lichen thalli remained constant at the conditionally background plot PMP 15 during the entire monitoring period (Table 1, Fig. 3). The marked deviations (roughness, browning and necrosis of the central areas of old thalli, and necrosis of the lobe ends) are solitary and are associated with the natural aging of individuals.

The data on changes in the morphological traits of *H. physodes* thalli under the impact of the development of bauxite deposits over a long period of time (16 years) allowed us to rank the response of lichen thalli from the initial acute stage to the period of adaptation to changed environmental conditions (Table 3). The lichen adapted to chronic dust pollution presumably 10–12 years after the beginning of exposure.

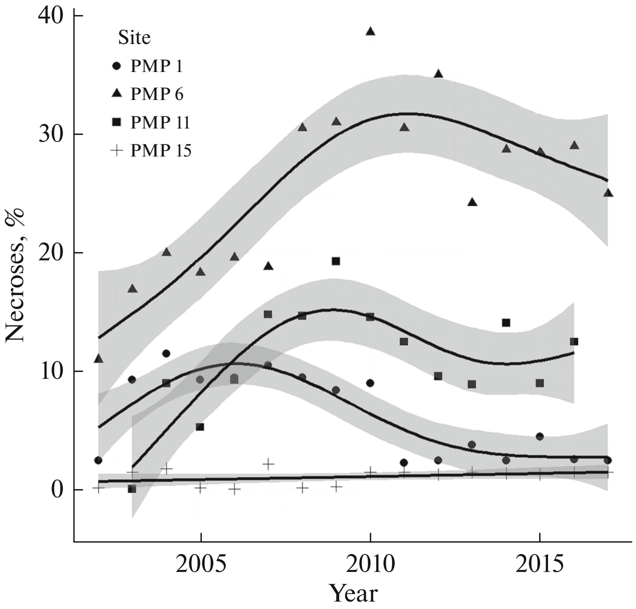

Fig. 3. Change in the area of necrosis (%) of the upper cortical layer of thalli of the lichen *Hypogymnia physodes*. See designations in Fig. 2.

The data on the change in the projective cover of lichen on spruce trunks under the impact of dust pollution confirm the patterns revealed during the study of morphological damages of *H. physodes* thalli (Fig. 2).

At the initial stage of monitoring, the mass die-off of thalli in the zone of strong pollution (PMP 6) promoted a sharp decrease in the projective cover of *H. physodes*. This parameter reached a minimum in 2010, 2.7 points (i.e., the cover was less than 3%). Since 2011, despite the increasing volumes of bauxite ore mining, there was a positive trend due to the formation of compact thalli more adapted to dust deposition.

The projective cover decreased not as sharply at plots with a medium level of pollution (PMP 1 and PMP 11) (Fig. 2). Since 2011–2012, its gradual recovery has been observed. The analyzed parameter is stable for all 16 years of monitoring at the conditionally background plot (PMP 15).

Thus, a decrease in the projective cover of the lichen *H. physodes* and numerous morphological damages to its thalli were recorded in the areas located near the production facilities of the MTBM. The most significant changes were observed in the first years of monitoring; in 2011 and 2012 the considered parameters began to stabilize, and then improve. In our opinion, this is due to the adaptation of lichen to chronic dust pollution.

Table 3. Changes in morphological traits of thalli of the lichen *Hypogymnia physodes* under the effect of dust pollution

Initial (shock) period in: 2002–2006	Period of maximum changes: 2007–2011	Period of adaptations: 2012–2017
Change in thallus color (pinkish, brownish spots, chlorosis). Roughness, sometimes cracking of the upper cortical layer, necrosis of central areas of thalli and mass die-off of lobe ends. Die-off of old thalli (few). Necrosis 10–15%	Severe roughness, thickening and ruptures of the upper cortical layer, formation of uncharacteristic outgrowths (papillae and lobules) and malformed thalli, necrosis of central areas of old thalli and mass die-off of lobe ends, infection with lichenicolous fungi, formation of shortened lobes, decrease in thalli sizes. Necrosis 15–20 (30–40)%	Small compact thalli prevail in the population. Roughness, chlorosis and necrosis (mainly point, rarely in central areas of thalli) of the upper cortical layer, necrosis of lobe ends, formation of lobules, infection with lichenicolous fungi, suppression of vegetative reproduction (formation of soredia). Necrosis 10–15(30)%

The study of the dynamics of the content of elements showed that, during the operation of the MTBM, the accumulation of elements such as Al, Fe, Ni, Cu, and Pb occurs in the thalli of epiphytic lichens. The content of Mn and Zn was high from the beginning of monitoring even in the background area, which can be explained by the geochemical features of the study area. The accumulation of these elements was not observed during the monitoring period. According to the content of metals in lichens at polluted PMPs, they can be arranged in a series: Al > Fe > Mn > Zn > Ni > Cu > Pb.

In the first decade of environmental monitoring, the rate of accumulation of the analyzed elements (Fe and Al, to a lesser extent Pb, Ni, and Cu) at medium and strongly polluted plots was higher than in subsequent years. Thus, the content of Fe and Al at the most polluted PMP 6 increased by 6 and 11 times from 2002 to 2011, respectively, and only by 1.8 and 1.3 times from 2012 to 2017, despite an increased volume of ore mining. The observed trend is shown in Table 2: differences in the accumulation of Fe and Al by lichens between the first (2002–2006) and second (2007–2011) periods are significant at $p < 0.01$ and, between the second and the third (2012–2017) periods, at $p < 0.05$.

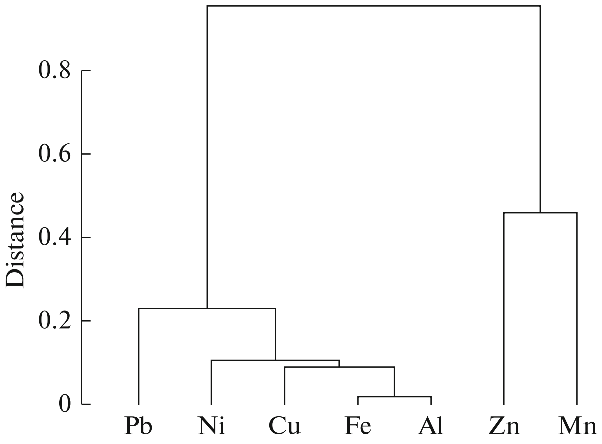

Fig. 4. Dendrogram of the correlation between the accumulation of elements in thalli of the lichen *Hypogymnia physodes*.

The decrease in the accumulation rate of many metals in lichens in the third period is apparently due to the limited abilities of lichens to biological accumulation of chemical elements and the peculiarities of the chemical composition of dust released from the bauxite mine (Golovko et al., 2018). When polluted with dust, a significant part of the metal compounds entering the environment (primarily Fe and Al) is represented as oxides with low solubility. Solid particles of fine dust settling on lichens remain on their surface and can be washed away by precipitation. When studying washout samples in laboratory conditions, it was found that, in epiphytic lichens collected at the polluted plots, most of Fe and Al (about 90%) was localized in the dust fraction that accumulates on the surface of the thalli and in the residual fraction (between loosely located fungal hyphae and algae cells). Only a small amount penetrated into the cells of symbionts (Golovko et al., 2018).

The cluster analysis confirmed the established differences in the accumulation of metals in the thalli of *H. physodes* over time (Table 4, Fig. 4). Two main groups of clusters with similar characteristics were identified. The first group includes five elements (Al, Fe, Ni, Cu, Pb) that show similarity in accumulation; of these elements, Al and Fe are most closely related, as is evidenced by a high value of the Pearson correlation coefficient (0.98 at $p < 0.01$). The second group includes Zn and Mn; the closeness of the relationship between them is also statistically significant, but much lower (correlation coefficient 0.54 at $p < 0.05$). The accumulation of these elements was not observed during the monitoring period.

CONCLUSIONS

According to the results of lichen indication studies on the example of the epiphytic lichen *H. physodes* on the territory of the MTBM, it can be concluded that this species is quite sensitive to pollution, with dust emitted as a result of bauxite mining. A decrease in its projective cover, an increase in the proportion of

Table 4. Pearson correlation coefficients between the content of elements in *Hypogymnia physodes* thalli

	Cu	Pb	Zn	Ni	Mn	Fe	Al
Cu		**0.69**	–0.26	**0.88**	0.19	**0.92**	**0.90**
Pb	0.000		–0.06	**0.80**	0.38	**0.80**	**0.79**
Zn	0.056	0.685		–0.26	**0.54**	–0.19	–0.21
Ni	0.000	0.000	0.050		0.28	**0.92**	**0.89**
Mn	0.164	0.004	0.000	0.035		0.32	0.27
Fe	0.000	0.000	0.155	0.000	0.017		**0.98**
Al	0.000	0.000	0.117	0.000	0.042	0.000	

The Pearson correlation coefficients are given above the diagonal, and the corresponding significance levels are shown below the diagonal. Significant coefficients ($p < 0.01$) are in bold.

necrosis of thalli, and a decrease in their linear dimensions were observed.

The study of the dynamics of the content of the main pollutants in lichen thalli showed that, during the operation of the mine, the Al and Fe prevailing in dust deposits were characterized by a large accumulation. The long period of monitoring studies (16 years) allowed us to establish that the ability of lichens to biological accumulation of chemical elements in conditions of dust pollution is limited. The data on the change in the content of metals in thalli of the lichen *H. physodes* are consistent with the periodicity of the response of lichen thalli to pollution.

Based on the above, the conclusion is made about the formation of a new adaptive mechanism in lichens under conditions of dust pollution, which increases the threshold of resistance to negative environmental factors.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest.

All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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