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Effect of artificial pollution by industrial dust on soil and vegetation in Northern Taiga (Russia)

Irina Lyanguzova*, Vadim Gorshkov, Irina Bakkal

Laboratory of Plant Communities Ecology, V.L. Komarov Botanical Institute, Saint-Petersburg, 197376, Russia

Abstract

A field experiment was laid out in 1997 in the background a pine forest (67°51'00" N, 31°24'30" E). Industrial dust sampled from electric filters of ore smelting department of copper-nickel plant was scattered on the surface of the snow cover. Scattering of industrial dust manually led to spatially very uneven pollution of Al-Fe-podzolic soil and destruction of ground cover. In 2011, the projective cover and height of all species of dwarf-shrub–herb and moss-lichen layers were measured in 50 sites, also there were sampled leaves of *Vaccinium vitis-idaea*, live parts of lichens *Cladina mitis, Cl. rangiferina, Cl. stellaris, Cladonia uncialis* and forest litter as well. Litter samples were analyzed by scanning electron microscopy with X-ray microanalysis (SEM/EDX), X-ray fluorescence (XRF) and atomic absorption spectrometry (AAS). The plant material was analyzed by AAS.

According to the SEM/EDX, particles of ashing samples of litter are mainly represented by various soil-forming minerals and iron oxides; about 10–15% of the particles have a spherical shape. They are often mounted by smaller particles consisted of salts and oxides of heavy metals, arsenic and selenium. The shape and surface morphology of spherical particles and their chemical composition are typical for melt drops, entrained by gas discharging flows from smelters. According to XRF data, the litter's ash mainly consists of SiO_2, Al_2O_3, CaO, MgO, K_2O and is enriched by Ni, Cu, Zn, Pb, Sn, As, Sb, Se. The total content of Co, Ru, Rh, Pd, Ag, Cd, Te, Os, Ir, Pt, Au in all samples was below the detection limit of the XRF method. In samples of litter only 12–24% and 29–39% of the total content of Ni and Cu were in mobile forms.

As a criterion for assessing the level of pollution of habitats the technogenic load index (I_l) was adopted. I_l reflects the excess of the total content of mobile forms of Ni and Cu in the litter over their content in the background. State of the dwarf-shrub–herb layer of experimental Pine forest was not disturbed in the interval I_l = 2.3–86 rel. un. At I_l ≤10 rel. un. moss-lichen layer was normally developed; in the interval I_l = 10–30 rel. un. it was disrupted to varying degrees; and completely

*Corresponding Author: irina@lya.spb.ru

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destroyed at I_l >30 rel. un. Between I_l and the projective cover of each lichen species and their total cover was a significant negative correlation [$r = -(0.56-0.73)$, $p < 0.05$]. No correlation was found between the content of heavy metals in the leaves of dwarf-shrubs or live parts of lichens and the projective cover or height of all species.

Keywords: Heavy metals; industrial dust; Al-Fe-podzolic soil; Northern Taiga; dwarf-shrub–herb and moss-lichen layers.

Introduction

Nowadays anthropogenic pollution remains one of the most urgent problems of the modern world, in spite of the fact that many countries make much effort to reduce the emission into the atmosphere of pollutants. Air emissions of the ferrous and non-ferrous metallurgy enterprises consist mostly of sulphur dioxide and heavy metals, as a result of complex influence of which, the forest ecosystem's destruction occurs, right up to the formation of technogenic heaths (Wotton et al., 1986; Norin & Yarmishko, 1990; Lukina & Nikonov, 1996; Lukina & Chernenkova, 2008; Salemaa et al., 2001; Myking et al., 2009; Yarmishko et al., 2009; Lyanguzova, 2010; Evdokimova et al., 2014). But in conditions of sulphurous anhydride together with polymetallic dust aerotechnogenic pollution it's impossible to divide the toxic effect of sulphur dioxide and heavy metals on the forest ecosystems. In this connection a field experiment, conducted to investigate the effects of heavy metals on plant communities and soil, was founded in the Kola Peninsula background area, where there are no visually observable plants' damages.

The aim of this work is to study transformation of the industrial dust particles in the organic horizon of Al-Fe-humus-podzolic soil, as well as assessment of the impact of the ecotope pollution level on the state of the dwarf-shrub-herb and moss-lichen layers of lichen pine forest in the Northern taiga subzone.

In 1997 control and experimental plots (67°51´00´´ N, 31°24´30´´ E) with a total area of 0.2 hectares, were laid in the lichen pine forest of the Kola Peninsula on uncontaminated territory. 43.3 kg of polymetallic dust, taken from the electrostatic precipitators of copper-nickel plant's ore electric smelting shop (Murmansk region, Russia), was manually disseminated on the snow cover of experimental plot with an area of 0.1 ha.

The scattering of polymetallic dust has led to very uneven spatial pollution of Al-Fe-podzolic soil and destruction of ground cover. In 2011 50 accounting sites with the size of 50x50 cm were founded in areas with different degree of destruction of the moss-lichen layer, the gradation of total projective cover of moss-lichen layer amounted to: 0-10, 11-30, 31-60, 61-80, 81-100%. Projective cover and height of all species of ground cover were measured for all accounting sites; also soil samples for genetic horizons, leaves *Vaccinium vitis-idaea* and lichen thalli *Cladina mitis, Cl. rangiferina, Cl. stellaris, Cladonia uncialis* were taken.

Litter samples were analyzed by using raster electron microscopy with X-ray microanalysis (SEM/EDX), X-ray fluorescence (XRF) and atomic absorption spectrometry (AAS). The plant material was analyzed by the method of AAS. Mobile fractions of Ni, Cu, Co were defined in the 1.0 N HCl extract from litter samples and mineral soil horizons using AAS method and the index of technogenic load was calculated (I_l). The latter is the excess of the total content of Ni, Cu and Co mobile fractions in the litter on their background content.

The material of ash-laden samples of forest litter from control and experimental plots has similar outward structure signs: it is a heterogeneous powdery brown substance with visible to the naked eye inclusions of large particles, various shapes and colors.

According to SEM/EDX, the basis of samples (over 85%) consists of a particles with the size of less than 50 microns; most of the particles have fission-fragment form, sharp edges, developed or smooth surface, which is typical for soil-forming minerals' particles formed in the natural conditions. In the samples of litter from experimental plot there is a small amount (10–15%) of particles with strictly spherical form and a smooth surface, the size of which does not exceed 6 microns. On the surface of some spherical particles there are aggregated smaller micro particles, which contain heavy metals, particularly Cu, Zn, Ni, Co, Sn. Such form and the surface morphology are typical for particles of dust from vents of matte smelting or ore smelting kilns. Therefore, it can be argued that by now some amount of polymetallic dust's particles, put in soil 14 years ago, has undergone no change.

Litter samples particles from control and experimental plots consist of soil-forming minerals and ferric oxides. In the control sample the basic elements are Si, O, Fe, Al, sometimes it is Ca, secondary are K, Mg, Na and as impurity elements there are S, Ti, Cl, Zn, Ba. The material of all the explored samples of experimental site's litter is similar in its total constitution. As impurity, and sometimes minor or major elements of the particles are Cu, Ni, Pb, As, which are completely absent in particles from control sample litter.

According to XRF of mineral residue samples of forest litter from control and experimental plots, there are differences in gross content of chemical elements. If in the control sample the chemical elements stand in the following descending range: Fe>S>Sn>Ti>Cl>Zn=Ba>Ni>Cu>As=Pb, the experimental samples of the plot have the following order of the elements: Fe>S>Cu>Ni>Sn>Zn>Ti≥Cl>Sb>Pb>Ba>As>Se. The gross content of Cu (on average in 100 times), Pb (in 55 times), As (in 33 times), Ni (in 22 times), Zn (in 5 times) and Fe (in 2.2 times) is increased dramatically especially in the last samples.

According to the data of Table 1, the highest content of mobile fractions of Ni, Cu, Co is detected in litter samples of both plots. In litter samples of experimental site their content in 21, 29 and 5 times higher than the corresponding control values. The content of Ni, Cu and Co in mineral soil horizons ranges from 0.5% to 10% of their concentrations in the samples of the litter. This implies that over 80% of mobile fractions of heavy metals are concentrated in the forest litter of contaminated podzolic soil, which, as everybody knows, is biogeochemical barrier on the way of pollutants into the soil profile (Lukina & Nikonov, 1996; Lyanguzova, 2010; Koptsik, 2012).

Table 1. Mean content (mg/kg) of mobile fractions of Ni, Cu, Co in samples of different soil horizons of control (1) and experimental (2) plots.

Soil horizon	**Content of metals mobile forms, mg/kg**					
	Ni		**Cu**		**Co**	
	1	**2**	**1**	**2**	**1**	**2**
Forest litter (A_0A_1)	6.7±0.1	140±14	9.5±0.1	280±20	1.1±0.1	5.8±0.6
Podzolic (A_2)	<0.5	12.9±0.5	<0.5	27.8±0.9	<0.5	1.0±0.1
Illuviale (B)	<0.5	0.8±0.1	<0.5	2.6±0.2	<0.5	0.6±0.1

At accounting sites of the experimental plot technogenic load index varies in the range of 2.3–85.8 rel. units, which corresponds to the total concentration of mobile fractions of Ni, Cu and Co from 36.5 to 1390 mg/kg of the litter.

Within the analyzed sample along the gradient of the degree of disturbance of moss-lichen layer the total projective coverage of the dwarf-shrub–herb layer and coverage of specific species varies within narrow range, and definitely don't change (table 2). The correlation coefficients between the projective cover of species and levels of heavy metals in the litter are insignificant, r = (0.15 – 0.21), P >0.05.

The total projective coverage of moss-lichen layer on the accounting sites of experimental plot varies widely – from 1.5 to 97%. With the technogenic load index $I_l \leq 10$ rel. unit moss-lichen layer develops normally: projective cover varies from 67 up to 97% and on average is 88 ± 3%, layer height is 8 – 10 cm. In the interval of technogenic load index I_l = 10 – 30 rel. unit – layer is disturbed to varying degrees: the projective cover varies from 24 to 92% and on average is 60 ± 4%, layer height – 4 – 8 cm. When I_l >30 rel. unit – the layer is destroyed: the projective cover varies from 1.5 to 33% and on average is 16.5 ± 3.2%, the average height of the layer is 1 – 2 cm. The dependence of the total projective cover of moss-lichen layer from the technogenic load index can be approximated in linear regression equation (the equation coefficients: 80.5 and –1.06, r = –0.76, P = 0.000).

Table 2. The projective cover (%) of on-soil vegetation on experimental plot.

Layer, species	**Gradation of the total projective cover of moss-lichen layer at accounting sites, %**				
	0–10	**11–30**	**31–60**	**61–80**	**81–100**
	Mean value of technogenic load index, rel. un.				
	58.9	**26.4**	**19.5**	**14.9**	**10.0**
Dwarf-shrub-herb layer, total projective cover	6.7±1.4	16±3.7	12±3.5	13±3.2	8.5±1.8
Empetrum hermaphroditum	1.0±0.3	5.6±2.5	4.8±2.3	1.3±0.6	0.9±0.6
Vaccinium myrtillus	0	1.4±1.3	0	1.5±1.4	0.3±0.3
Vaccinium vitis-idaea	4.5±1.0	5.4±1.2	5.6±1.3	8.3±2.0	5.1±1.2
Lichens, total projective cover	14.8±3.5	30.4±3.3	55.5±3.6	70.8±2.7	84.6±2.7
Cladina mitis	2.1±0.5	7.4±2.0	9.7±2.0	13.3±1.9	22.5±4.6
Cladina rangiferina	1.4±0.5	6.5±1.9	20.7±3.2	32.7±1.7	32.9±5.5
Cladina stellaris	0.8±0.3	3.3±0.6	7.5±1.8	12.4±2.3	18.2±4.4
Cladonia uncialis	0.9±0.5	1.0±0.3	5.2±1.4	6.2±1.3	9.0±2.5
Cladonia cornuta	0.8±0.3	2.6±1.3	1.1±0.3	1.2±0.7	0.3±0.1
Cladonia crispata	0.3±0.1	1.8±0.4	2.8±0.9	1.4±0.2	1.0±0.2
Cladonia deformis	0.7±0.2	1.2±0.8	0.5±0.2	0.2±0.1	0
Cladonia gracilis	1.3±0.5	0.6±0.2	0.7±0.3	0.7±0.3	0.1
Cladonia spp.	7.6±2.0	5.6±1.3	5.1±1.4	1.6±1.0	0
Trapeliopsis granulosa	0	0.8±0.6	0.5	0.1	0
Mosses, total projective cover	1.6±0.6	2.5±1.0	0.8±0.3	3.1±1.4	3.6±0.9
Dicranum scoparium	0	0.4±0.1	0.8±0.6	0	0
Hepatica spp.	1.1±0.2	2.4±0.6	1.2	3.6±1.3	3.1±0.7
Pleurozium schreberi	0	2.2±1.3	0.3±0.1	0.4±0.1	0
Pohlia nutans	1.4±0.7	1.7±0.9	0.9±0.7	2.0±1.2	1.2±0.4
Polytrichum piliferum	1.0	0.1	0.1	0.9±0.7	1.3±0.5

There is a significant negative correlation between the technogenic load index and total projective cover of lichens and cover of lichens *Cladina mitis, Cl. rangiferina, Cl. stellaris, Cladonia uncialis*, the correlation coefficients ranged from –0.56 to –0.73 (P <0.05). Projective cover of the initial lichen thalli positively correlated with the technogenic load index (r = 0.51, P <0.000). There is no correlation between other species of lichens as well as all species of mosses and the technogenic load index.

The average content of Ni and Cu in the leaves of *Vaccinium vitis-idaea* at the control plot is within the normal of their content for plants. In the experimental area average content of Ni almost in 5 times, and Cu – only in 1.3 times higher than the corresponding background concentration (Table 3). The increase in the concentration of the studied heavy metals in shrubs' leaves caused by their root uptake from contaminated forest litter. The absorption rate and movement of nickel ions from the soil in assimilation organs significantly higher than that of copper ions.

Table 3. Mean content (mg/kg of dry material) of heavy metals and its variation range in dwarf-shrub leaves and live parts of lichens thalli at control (1) and experimental (2) plots.

Species	**Content, mg/kg**			
	Ni		**Cu**	
	1	**2**	**1**	**2**
Vaccinium vitis-idaea	1.3±0.2	6.3±0.3 (2.2–11.2)	3.3±0.1	4.3±0.1 (2.9–6.1)
Cladina stellaris	2.0±0.2	2.5±0.1 (1.3–4.2)	2.1±0.1	2.7±0.1 (1.8–4.0)
Cladina rangiferina	1.8±0.1	2.1±0.1 (1.3–3.8)	1.0±0.1	1.9±0.1 (0.8–5.0)
Cladina mitis	2.7±0.1	3.6±0.2 (2.3–6.8)	1.6±0.1	2.0±0.1 (1.5–3.5)
Cladonia uncialis	1.4±0.3	2.3±0.1 (1.4–4.6)	1.7±0.1	1.8±0.1 (1.5–3.0)

At the control plot the interval of variation of Ni and Cu content in the living parts of thalli of 4 species of lichens (*Cladina stellaris, Cl. rangiferina, Cl. mitis, Cladonia uncialis*) rather narrow – from 0.9 to 2.8 mg/kg, and the average concentrations of heavy metals are within regional background values (Table 3). At the experimental plot the average content of both metals in almost all species of lichens is significantly higher with respect to their background concentrations. The highest values of the average content and scope variation of Ni are noted in the thalli of *Cladina mitis*, while similar figures for Cu are observed in *Cladina stellaris. Cladonia uncialis* has the lowest level of heavy metals at the experimental plot. In general, even the maximal concentrations of metals on average no more than 2 times exceed background levels in all investigated species of lichens. In almost all cases there is no correlation between the content of heavy metals in living parts of lichen thalli and forest litter. The high content of heavy metals in living parts of lichen thalli, apparently caused by pollution of soil particles under their windscreen transfer.

Thus, we can state that in 14 years after the introduction on the experimental plot some part of polymetallic dust is substantially transformed, moving from insoluble compounds in mobile fractions which are available to plants. Currently, the share of mobile fractions of Ni, Cu, Co average 20 – 30% of their total content. Another part of industrial dust remained unchanged, as evidenced by the presence in the forest litter experimental plot spherical particles, form and surface morphology of which are typical for micro particles of dust from vents of matte smelting or ore smelting kilns.

High or very high level of upper organogenic soil's horizon pollution with heavy metals and their high degree of availability for plants are the reasons of destruction of the moss-lichen layer on the territory of the experimental plot of a pine forest. Strong fixation of heavy metals in the organogenic horizon and their poor migration in mineral soil layers significantly slow down the processes of self-purification of contaminated soil and regeneration of dwarf-shrub-herb and moss-lichen layers of lichen type pine forests (Lyanguzova, 2010; Gorshkov et al., 2013).

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