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ECOLOGY

Multiyear Impact Monitoring of Pine Forests in the Central Part of the Kola Peninsula

V. T. Yarmishko[a], * and O. V. Ignateva[b]

[a]*Komarov Botanical Institute, Russian Academy of Sciences, St. Petersburg, 197372 Russia*
[b]*Kirov St. Petersburg State Forest Engineering University, St. Petersburg, 194021 Russia*
**e-mail: vasiliyarmishko@yandex.ru*

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Abstract—The spatiotemporal dynamics of structural and functional parameters of undamaged pine forests and those exposed to industrial emissions containing highly aggressive sulfur compounds in combination with heavy metals, Cu and Ni, were studied. The current condition of different components of undamaged pine forests is determined by natural succession processes. Technogenic air pollution is a significant factor in determining the life state of forest stands, and in the proximity of a large copper–nickel plant in the central part of Kola Peninsula, it is main factor causing weakening and even destruction of pine forest communities. There is a clear trend of improving life condition of the pine forests, even in the zone of strong pollution, on the background of significant reduction of emissions into the athmosphere.

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INTRODUCTION

There is a general increase in environmental changes connected with local and global impacts caused by intensive human economic activity in the course of historical development of society. It is increasingly more difficult to find vegetation communities undisturbed by natural and anthropogenic factors than sites of impact. This is the usual situation when most populations of a species are in relatively optimal conditions, but the environment begins to be changed. There is a need to assess the consequences of the development of organisms in nonoptimal conditions, the characteristics of the background condition, and the possibility of its definition as a conventional norm. To understand the real consequences of the observed environmental effects, it is necessary not only to fix certain deviations but also to find out the further fate of the changes.

Currently, one of the main factors that has a significant impact on functioning of forest ecosystems in northwestern Russia, after logging and fires, is industrial atmospheric pollution. In the central part of Kola Peninsula, the main source of emission is the Severonikel' Plant, which emits significant amounts of sulfur dioxide and heavy metals (Ni, Cu, etc.) into the environment. The negative impact of atmospheric emissions of this factory on plant communities has repeatedly been noted (Ramenskaya, 1974; Kryuchkov and Syroid, 1984; *Vliyanie*..., 1990; Lukin and Nikonov, 1996 1998; Yarmishko, 1997, 2009; Yarmishko et al., 2011; Yarmishko, V.T. and Yarmishko, M.A., 2015, etc.). A quarter of century ago, attempts were made at the plant to reduce industrial emissions significantly. In this regard, it could be assumed that the response of disturbed forest ecosystems would be a process of gradual recovery.

Our work aims at analysis of the materials of long-term monitoring of the pine forests in the central part of the Kola Peninsula and at assessment of their reactions to the reduction of air pollution.

MATERIALS AND METHODS

The Kola forest area is located within the boundaries of Murmanskaya oblast in the far north of Russia (Fig. 1). Geologically, the study area is the eastern Fenno–Scandinavian margin of the Baltic crystalline shield. The central part of Kola Peninsula is dominated by low-productive lichen and lichen–green moss pine forests. The main contribution to environmental pollution in the Kola North is made by acid-forming sulfur compounds and heavy metals entering the atmosphere as a part of emissions from the copper–nickel plant.

Severonikel' Plant in Monchegorsk (67°55′ N, 32°48′ E) began its activities in 1939 (Poznyakov, 1999). The maximum volume of emissions in a year, averaging 230000 tons of SO_2 and 15000 tons of polymetallic fine dust containing a mixture of sulfides and oxides of heavy metals, mostly Ni and Cu, was observed from 1973 to 1992 (Fig. 2). From 1993 to 1999, there was a tendency toward reduction of spe-

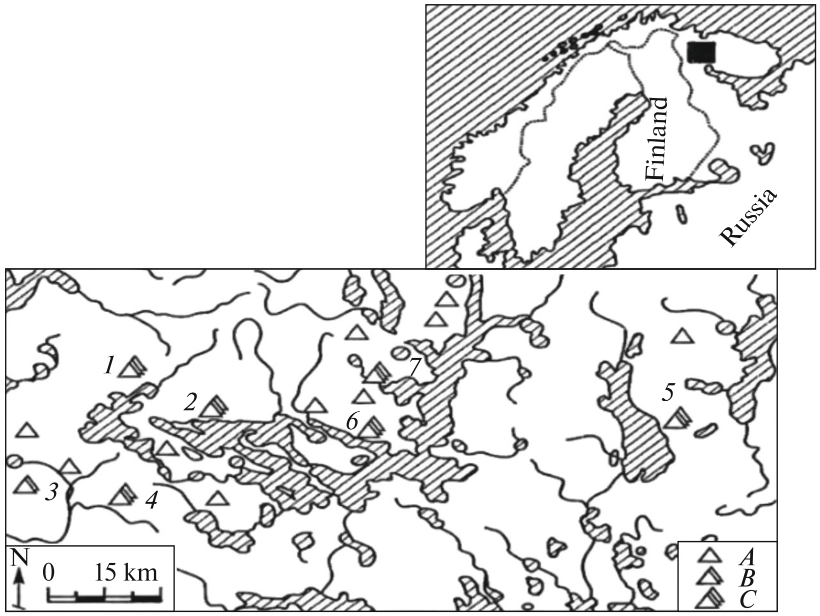

Fig. 1. Scheme of location of permanent sampling plots (PP) in pine forests on the Kola Peninsula. Main study areas: *1*, Livskii; *2*, Mavrinskii; *3*, Eno-Kovdorskii; *4*, Upolokshskii; *5*, Lovozerskii; *6*, Chunozerskii; *7*, Monchegorskii. Aquatic surfaces are indicated by hatching. *A*, single ones; *B*, 2–3; *C* > 3 PP.

cific and gross emissions of pollutants due to special environmental measures carried out by the plant. Since 1999, the annual volume of emissions has remained relatively stable at an average of 40000 tons of SO_2 and 5000 tons of polymetallic dust (*Ezhegodnik KMK*, 2007). These figures have changed little in recent years (Fig. 2).

Our studies were conducted from 1981 to 2017 in lichen–green moss middle aged (III–IV classes of age) pine forests situated at different distances from the plant in three areas: background, buffer, and impact. Permanent plots (PP) with a size of 0.15–0.2 ha were laid out in each area. Brief characterization of tree layers in the studied forest communities is given in Table 1. *Vaccinium myrtillus* L., *V. vitis-idaea* L., and *Empetrum hermaphroditum* Hagerup. dominate in the ground cover in the grass–shrub layer. The moss–lichen layer is formed by lichens of the genus *Cladonia* (*C. stellaris* (Opiz.) Brodo; *C. rangiferina* (L.) Nyl., and *C. mitis* (Sandst.) Hustich). Among mosses *Pohlia nutans* and *Hepaticae* spp. most often occur.

A complete census of trees was performed on each PP. Crowns and their conditions were measured, described, and assessed; the age of needles was determined, and their samples were taken for laboratory studies; categories of living conditions for all individuals of *Pinus sylvestris* L. in the tree layer were determined (Yarmishko, 1997; *Sanitarnye…*, 1998; *Metody…*, 2002). For determination of the age and analysis of radial growth of the wood in model trees, samples of wood (kerns) were taken by the Pressler drill or a trunk cut. The width of annual rings was determined on the LINTAB 6 device. In the process of research, we have developed and described new method of estimating the area of one-year radial growth for the example of the Scots pine (Lyanguzov etc., 2017). It was developed using close and not exactly measured values of the areas of the annual increment of the wood based on assumptions about the growth of wood of the trunks in the form of concentric rings.

The life duration of *P. sylvestris* needles was determined in 120–150 individuals in the upper (on the 8th–10th whorls) and lower (on the 18th–20th whorls) parts of the crown on the southern side on 3–5 shoots of the second order of branching. The area of needle damage by chloroses and necroses was estimated using a binocular microscope MBS-9 on 100 pairs of needles selected from shoots of the 2nd order of branching in 5–7 trees on each sampling plot (Yarmishko, 1997; *Dinamika…*, 2009).

Census and assessment of the condition of undergrowth were carried out on all PP (they were preliminarily marked in areas of 10 × 10 m). The characteristics of the aboveground cover of the studied forest communities were determined on permanent experimental plots (20–25 per PP) of 1 × 1 m (*Metody…*, 2002). Statistical data processing was performed using dispersion and regression analyses (Zaitsev, 1984).

RESULTS AND DISCUSSION

Relatively young communities of *P. sylvestris* on the background areas of the Kola Peninsula have a num-

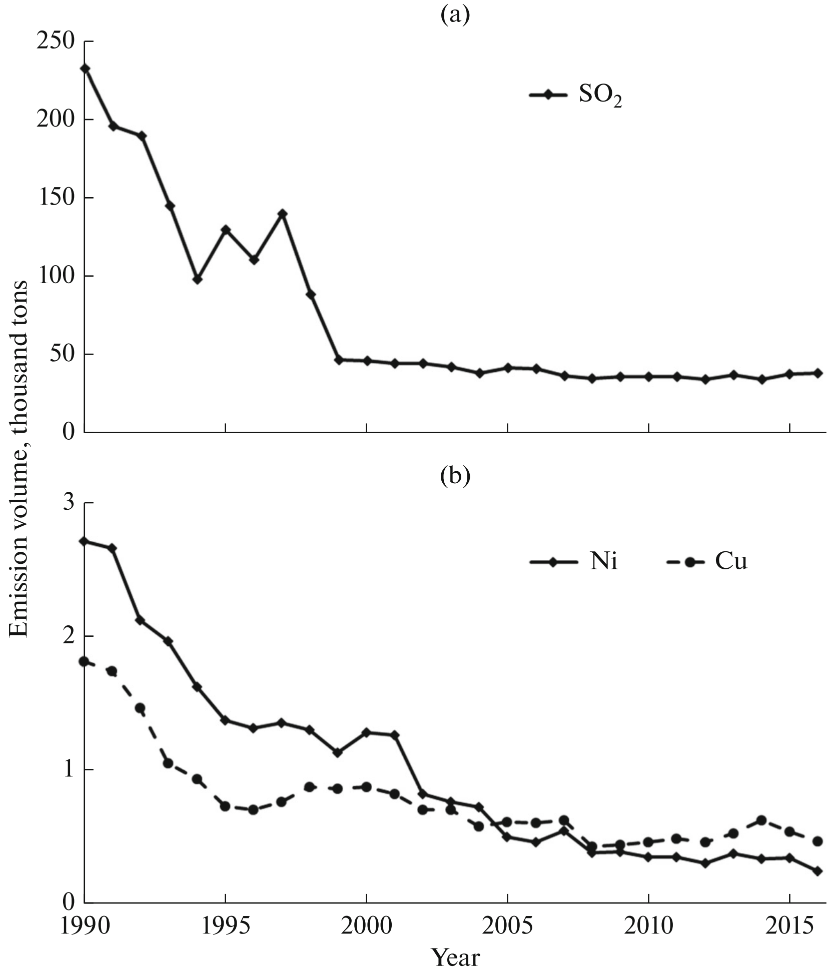

Fig. 2. Multiyear dynamics of atmospheric emissions of SO_2, Ni, and Cu, by data from the Kol'skaya Gorno-Metallurgicheskaya Company.

ber of features that distinguish them from similar stands formed in the European part of the northern taiga. First of all, this is the predominance of the main species over deciduous woody plants on a vast area in almost all types of forests, and the dominance of pine in most cases is manifested already at the stage of tree canopy formation. A characteristic feature of young pine stands is the participation of spruce and aspen in them.

In pine forests in the background conditions in the central part of Kola Peninsula in the organogenic horizon of Al–Fe–humus podzol soils, the content of mobile forms Ni and Cu is, on average, 10 mg/kg. These concentrations of heavy metals are taken as the background content (*Dinamika*..., 2009). In the 1- to 4-year-old needles of *P. sylvestris* and leaves of dominant undershrub species from 1981 to 2008, the Ni content changed from 16.1 to 1.5 and the Cu content dropped from 11.7 to 2.5 mg/kg of absolutely dry matter (ADM). These values are in the range of regional background concentrations and correspond to the normal content of these elements in plants (Ramenskaya, 1974; Lukina and Nikonov, 1996, 1998; Lozanovskaya et al., 1998).

A quite sensitive and easily determined indicator of the state of conifers is the life duration of needles on trees (Alekseev, 1990; Yarmishko, 1990, 1997, 2005; Tsvetkov, 1991; Stepanchik et al., 1993; etc.). The informativeness of this indicator is determined by the long duration of functioning of the assimilation organs of coniferous trees in the northern taiga communities, in which pine needles on trees remain 6–9, sometimes 10–12 years (Tsvetkov, 1991; Yarmishko, 1997; etc.). In the forests studied in the background conditions, the life duration of the *P. sylvestris* needles varied from 5.7 to 6.7 years for the whole observation period (Table 2). Fluctuations in the life duration of pine needles on sampling plots are connected mainly with differences in the weather conditions in some years.

Repeated detailed examination of the surface of needles at different ages allowed us to conclude that the indicators of the living condition of needles did not differ significantly in the studied periods of time.

Table 1. Brief characterization of the tree stands of the age classes III–IV in lichen–green moss forests in the conditions of different levels of aerotechnogenic pollution in the central part of Kola Peninsula, Murmanskaya oblast

PP location, coordinates*	Elevation above sea level, m; direction and steepness of slopes, deg	Distance to pollution source, km	Tree stand composition	Mean taxation characteristics of trees					Bonitet class
				height, m	diameter, cm	age, years	number of trees, specimens/ha	wood storage, m^3/ha	
67°33.227′ 31°04.751′	180, SW, 3°	70	10 P	8.5	10.1	50	1750	22.3	V
67°35.356′ 31°39.159′	161, SW, 2–3°	60	10 P	8.0	8.3	60	5273	47.5	V
67°38.168′ 32°42.234′	177, SW 5°	35	10 P	8.1	7.9	70	1852	32.0	V
67°49.216′ 32°46.447′	175, SW 4°	8	10 P	3.2	3.4	60	5300	10.1	V-a
68°00.384′ 32°55.540′	198, SW 10°	10	10 P, B	4.3	5.1	70	5450	21.8	V-a

* Upper lines mean N, lower ones E; SW, southwest; tree stand composition: P, Scots pine; B, birch (singly).

Table 2. Mean life duration of *Pinus sylvestris* needles on trees in pine forests of middle age in areas with different levels of atmospheric pollution on the Kola Peninsula

Year	Background area	Buffer zone	Impact zone
1982	6.0 ± 0.4	3.9 ± 0.8	2.4 ± 0.6
1987	5.7 ± 0.6	4.2 ± 1	2.5 ± 0.6
2005	6.4 ± 0.4	4.2 ± 0.7	5.3 ± 0.7
2008	6.7 ± 0.5	6.4 ± 07	5.0 ± 0.6
2014	6.2 ± 0.5	6.1 ± 0.5	5.3 ± 0.7
2017	6.3 ± 0.4	6.2 ± 0.6	5.3 ± 0.6

Under these conditions, only a small part (no more than 5%) of pine needles had chloroses and few points in the form of necrosis, which occupied <5% of the total surface (Table 3). On older needles (5–7 years) the area of visually observed changes in the color of needles sometimes reached 20% of the surface, which is apparently due to age-related changes in assimilation organs.

Middle-aged lichen–green moss pine forests in the background area are characterized by good growth and development; the trees are evenly distributed by the area, their number reaches, on average, 4000–4500 specimens/ha. Under their canopy are placed heavily suppressed live and dry pine individuals (2000–3000 specimens/ha).

Analysis of data on the radial increment of the pine indicated (Fig. 3a) that in the first 12–15 years of life, when there are no strict competitive relationships in the aboveground part and in the zone of root systems, it is characterized by sufficiently active growth in diameter, 1.2–1.5 mm/year and more. In the future, with the development of young pine and ground cover plants, the growth rate decreases by 23–25%, reaching >1 mm/year. Since the beginning of 1980s, this indicator has reached its minimum (0.6–0.8 mm/year) and has not changed for almost 20 years. According to the number of pine trees per hectare and the presence of thin and strongly oppressed individuals, it can be assumed that the processes of differentiation in the middle-aged pine forests will continue. Data in Fig. 3a reveal that short-term cycles of diameter increment fluctuations, which are obviously associated with changes in weather conditions, are clearly expressed in the study area. As a rule, they are synchronous in nature and vary slightly in the amplitude of fluctuations. The radial increment of the pine in recent years after some rise began to decline in all plots studied (Fig. 3a), which is associated, in our opinion, with the strengthening of competitive relationships in communities with age.

Table 3. Level of damage of *Pinus sylvestris* needles by chloroses and necroses in the conditions of various industrial atmospheric pollution. Upper lines are year 1998, lower ones 2014

Area of needle damage, %	Background area			Buffer zone			Impact zone		
	age of needles, years								
	1	2	3	1	2	3	1	2	3
<1	–	–	2	36	17	10	25	55	100
	–	–	1	26	5	5	18	20	35
1–5	–	–	2	31	56	56	37	46	100
	–	1	2	1	6	7	23	27	49
6–10	–	–	–	3	17	16	17	21	27
	–	–	–	–	–	–	3	13	22
11–25	–	–	–	–	9	16	12	38	36
	–	–	2	–	–	–	–	5	7
26–50	–	–	–	–	1	2	9	19	20
	–	–	–	1	–	–	–	–	–
51–75	–	–	–	–	–	–	–	3	7
	–	–	–	–	–	–	–	–	–
>6	–	–	–	–	–	–	–	13	10
	–	–	–	–	–	–	–	–	–

"–" means a lack of traces of needle damage.

In the background communities of *P. sylvestris*, located at a distance of 65 km or more from the Severonikel' Plant, there are no visual signs of damage to needles and crowns, so the vitalitic spectra of the pine stands were absolutely dominated by healthy individuals throughout the observation period (Table 4). The proportion of weakened individuals varied from 10 to 25.9%. In recent years (2008–2014), the vitalitic structure of stands of the Scots pine has deteriorated markedly: healthy individuals are 62–68%, weakened and severely weakened 24–30%, dry almost 4% (Table 4). As noted above, we associate marked deterioration in the life of the Scots pine stands on the PP in background conditions with strengthening of intrapopulation competitive relationships and, possibly, with global climate change.

Living ground cover in the background pine forests is well developed. The projective cover of the grass–shrub layer during the study period was 18% and did not change significantly as a result of multidirectional dynamics of individual species projective cover. The total projective cover of the moss–lichen layer also did not change and averaged 70–75%. We registered redistribution of the participation of early-, mid- and late-successional species of mosses and lichens in the formation of the above-ground vegetation cover. Coverage by early successional species of lichens *Trapeliopsis granulosa* (Hoffin.) Lumbsch, *Cladonia deformis* (L.) Hofifrn., *C. cornuta* (L.) Hoffm., C. *crispata* (Ach.) Flot., and *C. gracilis* (L.) Willd. during the study period decreased from 8 to 1%. Coverage of the mid- and late-successional species *Cladonia uncialis* (L.) Weber ex F.H. Wigg., *Cladina* spp., and *Pleurozium schreberi* (Brid.) Mitt. increased from 50 to 70%, while the projective cover of *P. schreberi* increased from 4 to 33% (*Dinamika*..., 2009). These changes in the moss–lichen layer were caused by strengthening of the environmental functions of the tree layer.

Thus, whole complex of changes observed in the background conditions of wood, grass–shrub, and moss–lichen layers in the studied lichen–green moss pine forests of middle age reflects natural succession processes in the recovery of communities after external disturbances such as logging and fires.

In the area of the middle level of technogenic pollution, in the buffer zone located 35 km from the main emission source, the content of acid–soluble forms of Ni and Cu in the upper soil horizons until 1997 was 4–8 times higher than the background values (*Dinamika*..., 2009), and the total content of these metals in the needles of *P. sylvestris* was 5–10 times higher than in the background communities. According to the data on 2008, their content decreased by three times in relation to the maximum values recorded in 1984–1988 (Yarmishko et al., 2011). Between the total concentration of Ni and Cu in the needles of *P. sylvestris* and emissions of solid substances by the Severonikel' Plant, there is a linear relationship: $r = 0.93$, $n = 6$, $P < 0.05$, where r is the correlation coefficient, n is the number of observations, and P is the significance level.

The life duration in *P. sylvestris* needles on the study area in the years 1982–1990 was significantly lower than in the background conditions and averaged four years (Table 2). The prevalence of intact needles (64%) was registered only for 1–2 years of age. In most

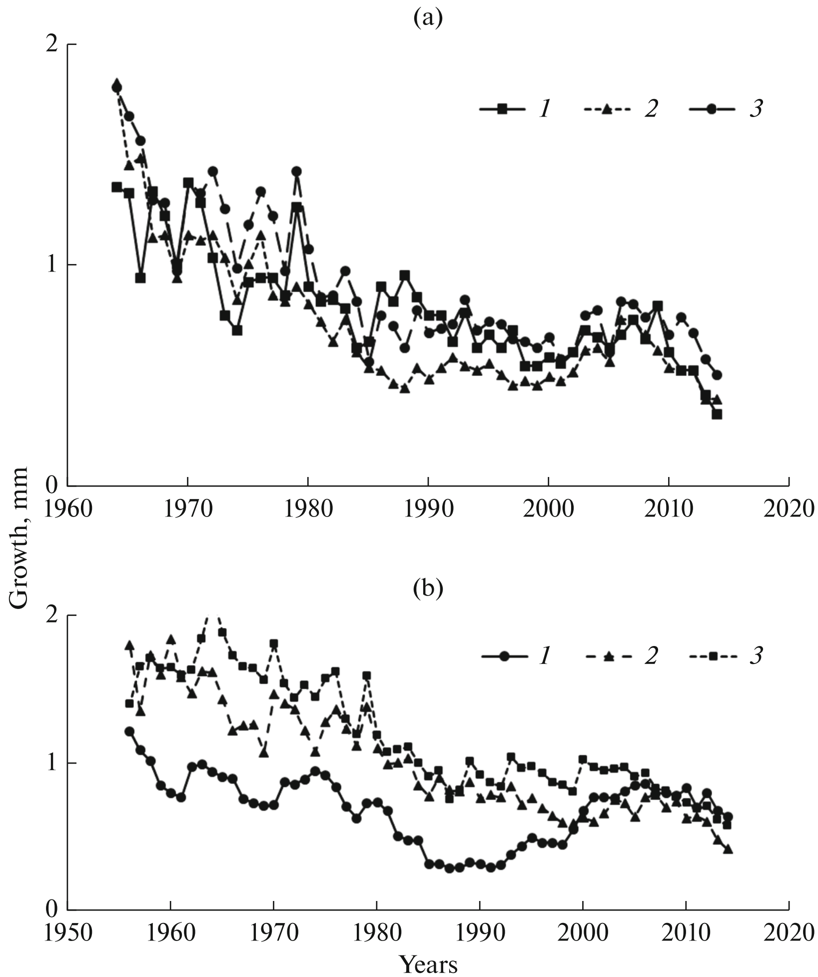

Fig. 3. Dynamics of the radial increment in *Pinus sylvestris* of age classes III–IV beyond the area influencing aerotechnogenic emissions of Severonikel' Plant (a) *1*, PP 20; *2* and *3*, PP 31 and 32 and in (*1*) impact zones, (*2*) background, and (*3*) buffer zones in the central part of Kola Peninsula (b).

of the three-year-old needles (56%), the area of damage was 1–5%. With increasing age of needles, the proportion of healthy needles decreases and the area of damage increases: 50% of four-year-old needles were covered with chloroses and necroses occupying 6–10% of the entire surface; a small part of the needles (2–3%) had necroses of red–brown color and healthy needles were absent (Table 3). Studies conducted in 2008–2014 showed that within the buffer zone, the main part of one-year-old *P. sylvestris* needles (93–98%) had no traces of damage. Spotty chloroses and point necroses of microscopic size, occupying 1–5% of the surface, were found only in a small part (~6%) of needles of 2–3 years of age. The proportion of healthy older needles was no greater than 78%. In 2008–2014, the condition of needles by life duration and the degree of damage reached almost background values (Tables 2, 3). There is a negative relationship between the life span of *P. sylvestris* needles and the annual atmospheric emissions of sulfur dioxide and solids ($r = -1$ and -0.97, $p = 4$, $P < 0.05$). A relationship between the heavy metal content in the needles of *P. sylvestris* and the duration of its life is absent.

The dynamics of the Scots pine growth classes III–IV in stands by years of age in conditions of different levels of technogenic pollution in the central part of the Kola Peninsula is shown in Fig. 3b. In the region of a moderate level of atmospheric pollution, the values of indicators of the wood radial increment until the beginning of the 1990s were close to similar values of indicators in control communities. Then the growth curve received a more distinct top–down character, in our opinion, because of the accumulation of pollutants in the community, especially in the soil, and the ongoing intrapopulation competitive processes in developing communities. Correlation analysis of the series of radial increments of the Scots pine in the regions of moderate pollution and emissions of gaseous substances clearly revealed (Yarmishko, 1997) a negative relationship ($r = -0.47$, $n = 24$, $P < 0.05$).

Table 4. Distribution of the *Pinus sylvestris* trees by categories of life condition on permanent sampling plots in the conditions of different levels of aerotechnogenic pollution in the central part of Kola Peninsula

Year	Categories of life condition of the Scots pine trees				
	healthy	weakened	strongly weakened	dry	total
Background area					
1985	79.2	18.7	0	2.1	100
1987	76.3	21.5	1.5	0.7	100
1990	80.1	15.3	1.8	2.8	100
1991	81.6	14.1	2.3	2	100
2005	89.7	10.3	0	0	100
2008	68.1	25.9	4.3	1.7	100
2014	62.1	20.5	13.6	3.8	100
Buffer zone					
1985	11.1	40.0	36.7	12.2	100
1987	4.9	54.9	25.6	14.6	100
1990	1.8	54	29.2	15	100
1991	8.3	29.5	45.5	16.7	100
2005	69.4	8.1	4.1	18.4	100
2008	61	17.1	4.8	17.1	100
2014	64.2	12.6	10.6	12.6	100
Impact zone					
1987	0	6.2	43.5	50.3	100
1990	0	8.1	42	49.9	100
2005	25.0	16.1	13.6	45.3	100
2008	21.3	28.7	9	41	100
2014	25.5	23.6	23.6	27.3	100

Studies conducted in recent years have shown that pine responded to the decrease in the emissions of toxic substances by intensifying growth in the early 2000s, by 10–15% compared to the previous period (Fig. 3b).

The results of our study on the vitalitic structure of the Scots pine communities in the buffer zone indicate that in 1981–1982 the proportion of healthy individuals did not exceed 50%; weakened ones, 31%; and strongly weakened and drying, 19%. By the early 1990s, the condition of pine stands deteriorated markedly: the proporiton of healthy individuals was 10–12%, the proportion of weakened was ~50%, and the proportion of severely weakened and drying trees was 20–25% (Table 4). At the same time, the proportion of dry trees increased by ten times as compared to that in 1982. Analysis of our data revealed that in the zone of mean levels of technogenic pollution the weakening of Scots pine trees has not yet reached the critical value, after which the edificatory role of the tree layer loses its importance in the community. Earlier it was noted that, in the case of significant reduction or cessation of environmental pollution in the area under consideration, pine forests can be restored naturally (Yarmishko, 2005). The results of studies conducted in recent years confirmed our assumptions. With a 4- to 6-fold decrease in the mean annual volume of atmospheric emissions of pollutants by Severonikel' since the beginning of the 2000s, the values of the life duration of needles approached the background values (Table 2), the intensity of damage also decreased significantly (Table 3). Reduction in pressure on the forest communities and, as a consequence, improvement of the condition of assimilation organs led to an increase in the proportion of healthy individuals in the vitalitic spectrum, which in 2008–2014 exceeded 60% (Table 4). The increase in the proportion of healthy trees was due to the transition of the weakened individuals to the category of healthy. As a result, the proportion of weakened trees on the PP decreased by almost four times compared to that in 1990 and amounted to 14%, and the proportion of severely weakened individuals decreased to almost 5% due to the transition of the trees to higher categories of living conditions.

In the ground cover of the studied pine forests in the buffer zone during the entire observation period, the values of the projective cover and the height of the grass–shrub layer did not differ significantly from the background ones, while the content of Ni and Cu in the leaves of dominant shrub species was 2–3 times higher than background concentrations (*Dinamika*..., 2009). The relationship between changes in the heavy metal concentrations in shrub leaves and emission dynamics, as well as the dynamics of acid–soluble Ni and Cu forms in the organogenic soil horizon, was not identified.

The condition of the moss–lichen layer remained significantly disturbed: the cover was dominated by early successional species, the coverage by climax species did not exceed 10%, which was five times less than in the background conditions. The mean height of the layer was 3 cm, which is 1.5–3 times less than the corresponding background values. The most disturbed condition of the layer was registered in 1994 in response to the 20–year period of maximum atmospheric emissions (1973–1992): complete absence of the main dominant in the moss cover of the background pine forests, *P. schreberi*, and minimal (1.5%) coverage of species from the genus *Cladina*. In 2006, the total projective cover of the layer remained at the level of 1994, but the coverage by climax species increased to 9%, which indicates a slight improvement in the condition of the layer in response to a sharp decrease in air pollution (*Dinamika*..., 2009). At present, early successional lichen species *T. granulosa*, *Cladonia* spp., and others still play the main role in the composition of the moss–lichen layer.

Analysis of the data obtained indicated that in the buffer zone the dynamics of the condition of the tree layer is determined by the regime of atmospheric emissions from the Severonikel' Plant. In our opinion, the condition of the moss–lichen cover is associated with the level of both atmospheric and soil pollution. It should be noted that the moss component of the studied communities is most sensitive to the complex effects of pollutants. The grass–shrub layer is resistant to the concentrations of environmental pollutants observed in the study area.

In the areas of heavy pollution (impact zone), the dynamics of the content of acid soluble forms of heavy metals in the organic horizon of soils was characterized by fluctuations independent of the atmospheric emission regime (Lyanguzova, 2009). The maximum concentrations of heavy metals in *P. sylvestris* needles, 20–40 times higher than the background values, were recorded in 1984–1988, and the minimal ones, 10–20 times higher than the background, in 2005–2008 (*Dinamika*..., 2009). The correlation coefficient between the contents of Ni and Cu in the needles of *P. sylvestris* and the annual solid emissions were 0.95 ($n = 6$, $P < 0.05$). The decrease in the total Ni and Cu concentration in the assimilation organs of *P. sylvestris* was conditioned by the decrease in the proportion of their air intake, because the level of contamination in the upper soil horizon remained sufficiently high.

The life duration of *P. sylvestris* needles in the impact zone during the observation period varied from 1.4 to 4.6 years (Table 2). Minimal values were recorded in 1987; maximum, in 2008–2014. The dynamics of the life duration of the needles is characterized by a negative relationship with the volume of emissions of sulfur dioxide and solids, in both cases $r = -1$ ($n = 4$, $P < 0.05$).

In 1988, only one-year-old needles of *P. sylvestris* were undamaged, and their proportion was 25% (Table 3). Two- and three-year-old needles were almost the same by the degree of damage: the latter was 20–40%. In 2008, the proportion of undamaged *P. sylvestris* needles gradually decreased with increasing age and amounted to 74, 55, and 12% for 1- to 3-year-old needles, respectively. At the same time, the area of chloroses and necroses of damaged needles did not exceed 10%. In general, despite significant improvement in the condition of the *P. sylvestris* assimilation apparatus by the end of the study period (2008–2014), the life duration was lower than the background values, and the degree of damage to it was higher (Tables 2, 3).

Throughout the observation period, the tree layer was characterized by a high degree of suppression in the impact zone. As in the buffer zone, the worst condition of the edifying sinusia of the forest communities studied was observed 15 years after the annual emissions reached their maximum values observed from 1973 to 1992. Against the background of subsequent reduction of the aerotechnogenic pressure, the condition of the pine forest tree layer gradually began to improve. It is important to note that in 2005 for the first time in the impact zone emergence of conditionally healthy *P. sylvestris* individuals in the tree layer was registered, which composed 25% (Table 4).

The radial increment of the Scots pine in the zone of severe pollution, within the radius of 8–12 km from the source of emission, at the beginning of the formation of stands was not characterized by a great intensity. It was 0.8–0.9 mm/year. Despite the great similarity of the growth curves in young communities in the conditions considered (top–down) with those in the background and in the buffer zone, the pine there has been significantly affected by pollutants since its settlement (Fig. 3b). The increase in the plant capacity and simultaneous start of the use of Norilsk ore in the 1970s, which differs from the local high content of S, were direct causes of a significant decrease (up to 0.3 mm/year) in the growth of pine in the area under study (Fig. 3b). The intensity of Scots pine radial growth in the area of heavy anthropogenic pollution gradually began to increase in the 1990s, reaching in the 2000s the values of its growth in two other areas studied. Correlation analysis of the series of the radial increment in the Scots pine in the areas of severe pollution reveals a sufficiently high negative relationship. A significant correlation exists both between the radial growth of pine and the amount of sulfur dioxide emitted into the atmosphere ($r = -0.8$, $n = 24$, $P < 0.05$) and the amount of solid particles ($r = -0.85$, $n = 24$, $P < 0.05$). It should be noted that there is a much closer relationship in the area of heavy pollution than in conditions of moderate industrial pollution. Here, the growth and development of individual trees and stands of the Scots pine depend more on the intensity of environmental pollution with sulfur dioxide and heavy metal oxides than on changes in climatic factors. However, also in the conditions under consideration, in our opinion, competitive relationships between plants should not be excluded. The density of pine stands there is still quite high, 3500–4200 per hectare, although they are largely damaged and weakened.

The results of the analysis of the vitalitic structure of the Scots pine communities in the impact zone indicated that at the beginning of our studies and until the end of the 1980s healthy pine individuals in the stand were not found, while weakened ones made up 6–8% and strongly weakened ones reached 42–43% (Table 4). Then, against the background of reduction of aerotechnogenic pollution from 1990 to 2005, the condition of pine stands began to improve markedly, and by 2005 the number of healthy individuals was 25%, while the proportion of weakened and severely weakened specimens was 16 and 14%, respectively (Table 3). At that time, dry individuals dominated the forest stand: ~45%. Recent studies have found no significant improvement in the health status of *P. sylvestris* communities. Transitions of individuals of some categories to higher ones were observed, which ultimately had a positive impact on the overall condition of the communities studied in the impact zone.

In the ground cover of the studied pine forests, the total projective cover of the grass–shrub layer decreased from 14 to 6% from 1984 to 2006. Its recent value is significantly different from the background ones. The negative reaction of the layer to the reduction in atmospheric emissions is associated with long-term exposure to high concentrations of heavy metals in the organogenic soil horizon, where the bulk of the roots and underground shoots of shrubs resides. The mean height of the layer during the study period was 7–8 cm, which is 1.5–2 times less than in the background area. The dominant layer during the entire period of research in contrast to the background communities was *Arctostaphyllos uva-ursi* L. The content of heavy metals in the leaves of shrubs by the end of the study period decreased on average by two times in relation to their maximum concentrations in this zone and in the leaves of *E. hermaphroditum* L. by more than ten times.

The moss–lichen layer during the observation period was in a completely destroyed condition: its projective cover was 10% and the height was 0.5 cm, which corresponds to 7 and 15 times less than the background values. Only early successional species participate in the formation of the cover. The general condition of the layer corresponds to the initial stages of recovery in the background areas recorded 5–10 years after the fire (Gorshkov and Bakkal, 2009). At the continuing level of aerotechnogenic pollution, the moss–lichen layer will remain in the completely destroyed state for an indefinitely long time.

Thus, within the impact zone, the dynamics of the life condition of the pine stands is determined by the level of aerotechnogenic pollution. In our opinion, the absence of significant positive reactions of grass–shrub and moss–lichen layers to the reduction of atmospheric emissions is conditioned by preservation of a high level of soil pollution with heavy metals.

CONCLUSIONS

The long-term impact monitoring of middle-aged pine forests in the central part of the Kola Peninsula showed that accumulation of heavy metals in the assimilation organs of plants of the tree layer can serve as a marker of the level of environmental pollution. The content of heavy metals in the leaves of the undershrub is not such indicator, obviously, due to the redistribution of dust particles coming from the air and from the tree layer and the soil surface.

In our opinion, the potential for recovery of plant communities depends on the scenario of further dynamics of the level of aerotechnogenic pressure: preservation of the volume of atmospheric emissions at the currently established level or the complete cessation of industrial emissions (plant shutdown). Currently, the characteristics of *P. sylvestris* needles in the buffer zone have reached background values, which indicates the possibility of gradual recovery of the tree layer of forest communities in these conditions.

Plants of the grass–shrub layer within the buffer zone, regardless of the scenario of dynamics of the level of technogenic pressure, remain in good life condition. In the impact zone, while maintaining the existing regime of industrial emissions, the layer will be in the presently significantly disturbed condition, since there is no reduction in the level of soil contamination with heavy metals.

The moss–lichen layer, while maintaining the current level of emissions and the level of heavy metals in the forest litter on the territory at the mean level of industrial pollution, will not be fully recovered.

In conclusion, it should be noted that, despite the minimal amount of atmospheric emissions established since 1999 (~40 000 tons of SO_2 and 5000 tons of polymetallic dust), it is currently incorrect to consider that the process of gradual recovery of severely damaged forest ecosystems in the vicinity of the Severonikel' Plant, the main source of emission, has started. Only one, though important, component of pine forest ecosystems, the tree layer, displays significant positive changes. The grass–shrub and moss–lichen layers, which displayed almost no reaction to emission regimes, remain in severely disturbed and destroyed conditions, respectively.

Existence of a relationship between the emission regime and the content of heavy metals in *P. sylvestris* needles, as well as its absence with the content of heavy metals in the leaves of undershrubs in the buffer and impact zones, indicate that the tree layer, even in the destroyed condition, retains its filtering function and intercepts the main amount of dust pollutants from the air.

The dynamics of different components of pine forests in the background conditions of the central part of the Kola Peninsula is conditioned by natural succession processes, in buffer and impact zones by the regime of atmospheric emissions and the content of heavy metals in soil.

COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

REFERENCES

Alekseev, V.A., Some problems in the diagnosis and classification of forest ecosystems damaged by pollution, in *Lesnye ekosistemy i atmosfernoe zagryaznenie* (Forest Ecosystems and Atmospheric Pollution), Leningrad: Nauka, 1990, pp. 38–54.

Dinamika lesnykh soobshchestv Severo-Zapada Rossii (Dynamics of Forest Communities of the North-West of Russia), St. Petersburg: VVM, 2009.

Gorshkov, V.V. and Bakkal, I.Yu., Lower storeys of coniferous forests, in *Dinamika lesnykh soobshchestv Severo-Zapada Rossii* (Dynamics of Forest Communities of the North-West of Russia), St. Petersburg: VVM, 2009, pp. 197–204.

Ezhegodnik KMK, Yearbook, 2007, no. 5.

Kryuchkov, V.V. and Syroid, N.A., Soil and botanical monitoring in the central part of the Kola Peninsula, in *Monitoring prirodnoi sredy Kol'skogo Severa* (Environmental Monitoring of the Kola Peninsula), Apatity: Kol'sk. Nauchn. Tsentr, Akad. Nauk SSSR, 1984, pp. 15–26.

Lozanovskaya, I.N., Orlov, D.S., and Sadovnikova, L.K., *Ekologiya i okhrana biosfery pri khimicheskom zagryaznenii* (Ecology and Biosphere Protection under Chemical Contamination), Moscow: Vysshaya Shkola, 1998.

Lukina, N.V. and Nikonov, V.V., *Biogeokhimicheskie tsikly v lesakh Severa v usloviyakh aerotekhnogennogo zagryazneniya* (Biogeochemical Cycles in Northern Forests under Conditions of Airborne Industrial Pollution), Apatity: Kol'sk. Nauchn. Tsentr, Ross. Akad. Nauk, 1996, vols. 1–2.

Lukina, N.V. and Nikonov, V.V., *Pitatel'nyi rezhim lesov severnoi taigi: prirodnye i tekhnogennye aspekty* (Nutrient Regime of the Northern Taiga Forests: Natural and Technogenic Aspects), Apatity: Kol'sk. Nauchn. Tsentr, Ross. Akad. Nauk, 1998.

Lyanguzov, A.Yu., Yarmishko, V.T., and Lyanguzova, I.Yu., A new method of estimating the annual growth of trunks of woody plants, *Rast. Resur.*, 2017, vol. 53, no. 4, pp. 580–593.

Lyanguzova, I.V., Dynamics of atmospheric emissions of an enterprise for the production of nonferrous metals and the accumulation of toxic substances in plants and soil, in *Dinamika lesnykh soobshchestv Severo-Zapada Rossii* (Dynamics of Forest Communities in Northwest Russia), St. Petersburg: VVM, 2009, pp. 25–58.

Metody izucheniya lesnykh soobshchestv (Methods of Study of Forest Communities), St. Petersburg: Nauchno-Issled. Inst. Khimii S.-Petesrburg. Gos. Univ., 2002.

Poznyakov, V.Ya., *Severonikel' (stranitsy istorii kombinata "Severonikel'")* (Severonikel (Pages of History of the Severonikel Industrial Comples), Moscow: Ruda i Metally, 1999.

Ramenskaya, M.L., *Mikroelementy v rasteniyakh Krainego Severa* (Trace Elements in Plants of the Far North), Leningrad: Nauka, 1974.

Sanitarnye pravila v lesakh Rossiiskoi Federatsii (Utv. prikazom Federal'noi sluzhby lesnogo khozyaistva Rossii ot 15.01.1998) (Sanitary Rules in Forests of the Russian Federation (Approved by the Order of the Federal Service of Forestry of Russia of January 15, 1998)), Moscow: Rosleskhoz, 1998.

Stepanchik, V.V., Tarasenko, V.P., and Vasilenko, A.I., Technogenic pollution of the Republic of Belarus and its impact on the pine plantations, in *Problemy lesovedeniya i lesovodstva: Nauchnye trudy Instituta lesa AN Belarusi* (Problems of Forestry and Forest Science: Scientific Papers of the Institute of Forest, Academy of Sciences of Belarus), Gomel, 1993, no. 37, part 1, pp. 62–70.

Tsvetkov, V.F., The state of forests exposed to industrial emissions in the Murmansk oblast and the problem of their conservation, in *Ekologicheskie issledovaniya v lesakh Evropeiskogo Severa* (Environmental Studies in the Forests of the European North), Arkhangel'sk: Izd. AILiLKh, 1991, pp. 125–136.

Vliyanie promyshlennogo atmosfernogo zagryazneniya na sosnovye lesa Kol'skogo poluostrova (Impact of Industrial Air Pollution on the Pine Forests of the Kola Peninsula), Leningrad: Bot. Inst. Ross. Akad. Nauk, 1990.

Yarmishko, V.T., State of the assimilation machinery of pine, in *Vliyanie promyshlennogo atmosfernogo zagryazneniya na sosnovye lesa Kol'skogo poluostrova* (Impact of Industrial Air Pollution on the Pine Forests of the Kola Peninsula), Leningrad: Bot. Inst. Ross. Akad. Nauk, 1990, pp. 55–64.

Yarmishko, V.T., *Sosna obyknovennaya i atmosfernoe zagryaznenie na Evropeiskom Severe* (Common Pine and Air Pollution in the European North), St. Petersburg: Nauchno-Issled. Inst. Khimii S.-Petesrburg. Gos. Univ., 1997.

Yarmishko, V.T., The crown of a tree as an indicator of its state under the conditions of technogenic pollution, in *Problemy ekologii rastitel'nykh soobshchestv* (Problems of Ecology of Plant Communities), St. Petersburg: VVM, 2005, pp. 28–57.

Yarmishko, V.T., Dynamics of the tree layer of pine (*Pinus sylvestris* L.) forests, in *Dinamika lesnykh soobshchestv severo-zapada Rossii* (Dynamics of Forest Communities in Northwest Russia), St. Petersburg: VVM, 2009, pp. 58–73.

Yarmishko, V.T. and Yarmishko, M.A., Radial growth of Scots pine (*Pinus sylvestris* L.) in varied environment influenced by air pollution in the European North of Russia, *Forestry Ideas* (Bulgaria), Sofia, 2015, vol. 21, no. 2 (50), pp. 96–105.

Yarmishko, V.T., Gorshkov, V.V., Lyanguzova, I.V., and Bakkal, I.Yu., Environmental monitoring of forest ecosystems of the Kola Peninsula under conditions of environmental pollution, *Region. Ekol.*, 2011, nos. 1–2 (31), pp. 21–29.

Zaitsev, G.I., *Matematicheskaya statistika v eksperimental'noi botanike* (Mathematical Statistics in Experimental Botany), Moscow: Nauka, 1984.

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