Chapter

Aerotechnogenic Pollution of Boreal Forests in Northern Europe

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Abstract

This paper discusses the changes that boreal forest ecosystems undergo under the influence of gaseous waste from the processing of non-ferrous ores on the Kola Peninsula. These communities are represented primarily by pine forests growing on the northern border of their range. The main forest-forming species here is Scots pine main components for this local aeronautical emission are polymetallic dust and sulfur dioxide, which is the main by-product during the roasting of sulfide and polysulfide ores. The studies were carried out on the basis of materials obtained at 6 sample plots located at different distances from the pollution source. As a result, an exponential increase in the content of heavy metals in the soil, as well as in the assimilatory organs of the components of these communities, was shown when approaching the source of pollution (this pattern is different for each of the metals). Regularities of negative changes in the structure of some components of plant communities, such as phytomass, projective cover of the lower layers, and the vital structure of the tree layer were also identified.

Keywords: northern taiga, boreal forests, pine forests, aerotechnogenic emissions, heavy metals, sulfur dioxide, nonferrous metallurgy

1. Introduction

At present, atmospheric pollution is one of the most pressing environmental problems. An actively developing industry inevitably has a negative impact on the fragile structure of biocenoses. It is not only natural communities in the immediate vicinity of industrial centers that are under threat. The development of the transport system [1, 2], tourism [3] and, in general, the improvement of the quality of life of the population of the region has a negative impact. However, the most noticeable man-made effect of a local nature (including aero-man-made one) is produced by large enterprises. This problem is especially acute in the Russian Federation, where one of the main source of income for the state is the extraction and primary processing of natural resources (cleaning of raw materials, remelting ores). Basically, such pollution is of a local nature, and exposure to toxic substances occurs only in the area associated with the enterprise, as evidenced by various studies [4–6]. This study was carried out on the territory of the Kola Peninsula, the Murmansk region, where, in addition to the main object of pollution: Monchegorsk mining and metallurgical plant "Severonikel", there are a number of other industrial pollutants (Kola NPP, Kandalaksha aluminum plant, Apatity plant of nonmetallic materials, mining and metallurgical plant "Pechenganikel"). However, such enterprises have insignificant local atmospheric pollution. In the taiga zone of

this region, the main plant communities are pine and spruce forests. Therefore, the species that make up such communities were selected by us as indicators of industrial atmospheric pollution.

At the moment, special attention is paid to assessing the level of pollution and assessing the state of plant and animal communities affected by this pollution. First of all, this is due to the general tendency to introduce such concepts as "ecological significance" and "environmental impact" into all aspects of our life. On the other hand, the very policy of the state develops in such a way that there is a shift in priorities from the predatory exploitation of natural resources to an attempt to maintain the ecological state of nature in a stationary primordial state and a model of sustainable development.

2. Aerotechnogenic impact on plant communities

To date, a significant amount of data has been accumulated on the impact of such emissions on the biocenoses of the Kola Peninsula. The effect of harmful effects on the layers in the community is especially pronounced in the areas where industrial enterprises are located. In these cases, toxic substances in the air form compounds that simultaneously affect different plant organs. The Severonikel Plant (Monchegorsk, Murmansk Region) is one of the largest non-ferrous metallurgy plants in the Russian Federation. The first permanent sample plots in the region were established in the 1970s. Since the second half of the 90s of the XX century, the plant has significantly reduced the amount of airborne industrial emissions (**Figures 1** and **2**), as evidenced by the data of various studies [7].

For several decades, atmospheric emissions have allowed toxic compounds to accumulate in biotic and abiotic components of the environment in the vicinity of the plant. The results of the analysis of various components of Scots pine (*Pinus sylvestris* L.) communities (soil, litter and various parts of plants) in the vicinity of the plant in the 1980s differed by almost two orders of magnitude from similar samples taken in the background areas, and were threshold for plant growth [8, 9].

Currently, special attention is paid to assessing the level of pollution and assessing the state of plant and animal communities subjected to this and similar pollution. First of all, this is due to the general tendency to introduce such concepts as "ecological significance" and "environmental impact" into all aspects of our life.

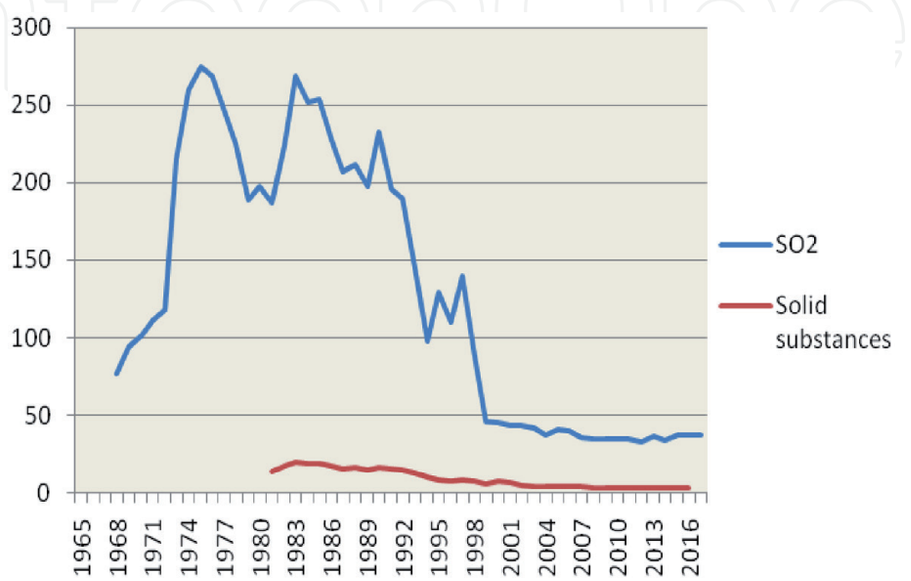

Figure 1.
Dynamics of the total volume of airborne industrial emissions from the Severonikel plant, thousand tons.

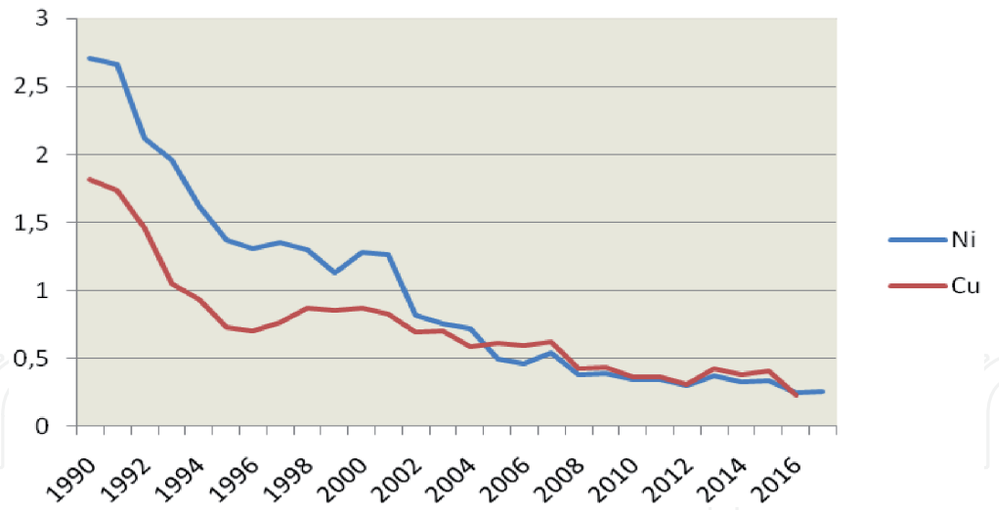

Figure 2.
Dynamics of heavy metals emissions from the Severonikel plant, thousand tons.

On the other hand, the very policy of the state develops in such a way that there is a shift in priorities from the active "predatory" exploitation of natural resources to an attempt to maintain the ecological state of nature in a stationary primordial state (according to the concept of sustainable development).

The progressive deterioration of the vital state and drying out of pine forests under the influence of industrial atmospheric pollution in almost all European countries, including Russia, is currently attracting special attention of researchers. Significant damage to pine forests is caused by uncontrolled accidental emissions even from relatively small industrial enterprises, in which the concentration of pollutants entering the atmosphere increases sharply. The influence of emissions is more distributed in the direction of the prevailing winds. On the basis of comprehensive and in-depth studies of the influence of industrial pollution on the growth, productivity and condition of Scots pine stands, methods and methodological approaches to assessing changes in forest phytocenoses under anthropogenic disturbances are proposed.

Studies have established that a decrease in the height gain in pine under the influence of air and soil pollution occurs much later than the manifestation of visual signs of damage to the assimilation apparatus of trees [10]. It was also found that the decrease in height gain and the process of top drying did not decrease with limited emissions [11]. This can be explained by the fact that the intensity of the drying process is due not only to the amount, but also to the concentration of harmful chemicals in the soil and tree tissues.

It was also found that the increase in diameter of 50-100-year-old individuals can serve as a reliable indicator of environmental pollution. These trees reduce the growth rate before serious damage or death of individuals occurs.

3. The main products aerotechnogenic emissions

Sulfur compounds.

These substances have an effect primarily on the assimilation apparatus of plants. The main atmospheric pollutant in this region is sulfur dioxide (SO_2), which, entering the leaves and needles through the stomata, turns into a highly toxic sulfite ion (SO_3^{2-}), which in turn is slowly oxidized to a less toxic sulfate ion (SO_4^{2-}). In addition to the selective effect on some enzymes and catalytic chains (disruption of the light and dark phases of photosynthesis, the effect on the state of chlorophyll,

changes in the lamellar structure of gran. These ions acidify the internal environment of cells, resulting in a decrease in the pH of the cytoplasm, stroma and matrix, which leads to a general disruption in the functioning of cells, resulting in the development of chlorosis and necrosis in needles.

Heavy metals.

Nickel. It is present in the plant as a Ni^{2+} ion. Nickel is a member of a number of enzymes, the most studied of which is urease, which is involved in the breakdown of urea. In addition, nickel activates the work of a number of enzymes (peptidases, nitrate reductases), stabilizes the structure of ribosomes, and influences the supply and transport of nutrients. There is still no clear evidence of nickel deficiency in plants. Under experimental conditions, the lack of metal causes disturbances in the metabolism of urea.

Copper. The question of the form in which copper enters underground and aboveground organs (Cu^{+}; Cu^{2+}) is currently under discussion. In plants, up to 98% of the metal is in an insoluble bound state. Seeds and growing parts of the shoot are relatively rich in this element. In the leaves, most of the copper is concentrated in chloroplasts and almost half in the composition of plastocyanin, one of the electron carriers between PS I and PS II. Most of the functions of copper are associated with its participation in enzymatic redox reactions. In addition, copper promotes the formation of chlorophyll and slows down its destruction in the dark. It affects nitrogen metabolism, being a part of nitrite reductase and nitric oxide reductases, and enhances the process of binding nitrogen molecules. Copper Functions in the cytochrome oxidase complex of the mitochondrial respiratory chain. It also contributes to the intake of manganese, zinc and boron into the body, increases drought, frost, and heat resistance, takes an active part in protecting against pathogens. Lack of copper causes a delay in growth and flowering, leads to a loss of turgor in the leaves. A high content of copper in plants can lead to a change in pigmentation (blackening of the petals of angiosperms, the copper content can reach 0.021%).

Cobalt. For a long time, cobalt was considered as an element necessary only for animals and microorganisms. Currently, it is referred to as the metals necessary for higher plants. In plants, cobalt is found in free ionic (Co^{2+}; Co^{3+}) and bound forms. It concentrates in the generative organs, accumulates in the pollen, and accelerates its germination. Cobalt enhances protein biosynthesis, regulates growth processes, removes the inhibitory effect of auxin on cell division and inhibits ethylene biosynthesis. In addition, cobalt is a part of vitamin B12 and increases immunity to certain diseases, takes part in redox processes, increases the content of pigments in leaves, which is associated with an increase in the plastid apparatus due to the replication and growth of organelles. Along with magnesium and manganese, cobalt activates the glycolysis enzyme phosphoglucomutase.

The main source of heavy metals entering the environment is technogenic. The mechanism of entry of heavy metals from the soil into plants by the root route includes passive (non-metabolic) transfer of ions into the cell in accordance with their concentration gradient and active (metabolic) absorption by the cell against the concentration gradient. Also, heavy metals in the composition of aerosols and dust fall on the sheet, are retained on it in the form of surface deposits, some can be washed out by rainwater, and some enter the plant [12].

The influence of heavy metals on physiological processes.

Growth. Growth inhibition is one of the most common manifestations of the toxicity of heavy metals to plants. In the presence of high concentrations of heavy metals, the intensity of cell division slows down, the number of cells decreases at all phases of mitosis, and the duration of individual phases and the entire mitotic cycle increases. In addition, heavy metals can slow down the presynthetic and postsynthetic stages of cell division.

A reliable relationship was found between the radial growth of tree trunks and the volumes of emissions from the plant entering the atmosphere, while the relationship is nonlinear and depends on the level of anthropogenic load on trees at different distances from the plant, on the species of trees and location on the slopes of hills. In particular, the response of pine to technogenic stress was revealed. Despite a significant decrease in emissions in recent years, the radial growth of trees in the impact zone continues to remain significantly less than the background values. The main reason is the high content of heavy metals in the organogenic horizon of the soil and the persisting atmospheric precipitation.

Photosynthesis. A decrease in the intensity of photosynthesis in plants in the presence of heavy metals is primarily associated with their negative effect on photosynthetic pigments. In the presence of heavy metals, a decrease in the content of chlorophyll a and b was found. At the same time, pronounced chlorosis is observed on the leaves. The main reason for this effect is the suppression of chlorophyll biosynthesis, which is associated with the direct action of heavy metals on the active centers of enzymes. It is also possible to expel magnesium ions from the chlorophyll molecule.

Disruption of the chloroplast ultrastructure in the presence of heavy metals is also one of the most important reasons for a decrease in the content of pigments in plants and, in general, for a decrease in the intensity of photosynthesis. So, under the action of nickel and copper in high concentrations, the number of plastoglobules in plants increases, which indicates an increase in the degradation of organelles. In addition, the number of grains decreases and their structure is disturbed. Grana become irregular and contain fewer thylakoids. Heavy metals directly affect the transfer of electrons in photochemical reactions. In addition, in the presence of heavy metals in plants, cyclic and non-cyclic phosphorylation slows down, and ATP synthesis is suppressed.

4. Material and methods

The studies were carried out on the basis of material obtained on the territory of the Kola Peninsula in Monchegorsk (buffer and impact zones) and Kovdorsk

№	Sample plot name	Distance from pollution source, km	Community age, years	Height above sea level, m	Coordinates
Impact zone					
1	10 O	10	80	158	N 68 00.384, E 032 55.541
2	29	15	80	162	N 67 44.216, E 032 46.447
Buffer zone					
3	3	25	80	169	N 68 06.817, E 033 19.455
4	27 O	35	80	165	N 67 38.168, E 032 42.234
Non-contaminated zone					
5	20	65	80	145	N 67 30.055, E 031 46.886

Table 1.
Location of permanent sample plots in the study area.

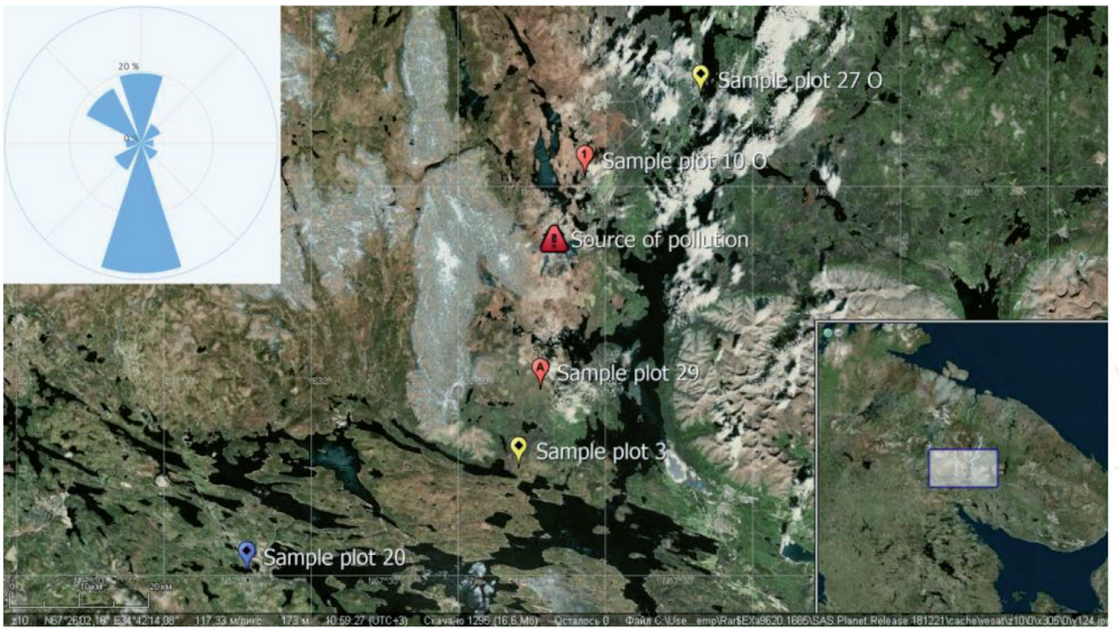

Figure 3.
Sample plots location map.

(non-contaminated zone) districts on 5 previously established permanent sample plots oriented along the pollution gradient from the emission source to the background in the northern and southern directions (**Table 1**, **Figure 3**).

On each trial plot, samples of the upper organic horizon of Al-Fe-podzol were taken in the amount of 5 samples for each trial plot, from which the undecomposed upper elements of forest litter were excluded. These samples were used to prepare a soil extract (extract with 1.0 N HCl solution), for which the content of acid-soluble forms of Ni, Cu, Co was further determined by atomic absorption spectrometry. Similarly, the content of heavy metals was determined in the assimilation organs of plants growing on these test plots (the tree layer and the undergrowth canopy were mainly formed by the species *Pinus sylvestris* L.; the herb-dwarf layer was formed by the species: *Vaccinium vitis-idaea* L., *Vaccinium myrtillus* L., Empetrum hermaphroditum Hagerup., *Arctostaphylos uva-ursi* (L.) Spreng.; moss-lichen layer is formed by species: lichens of the genus *Cladonia* (*C. stellaris* (Opiz.) Brodo, *C. rangiferina* (L.) Nyl., *C. mitis* (Sandst.) Hustich), *C. coccifera* (L.) Willd. and *Pleurosium schreberi* (Brid.) Mitt.). The work presents the average values of the available sample for these sample plots.

For the ground layers, the total projective cover of the species was determined, as well as the ground phytomass of plants. The characteristics of the tree layer were also obtained on these permanent sample plots. We assigned all individuals of the forest-forming species with a trunk diameter of 4 cm or more at a height of 1.3 m to the tier of the stand. For all individuals of the stand, trunk diameter, tree height and vitality class were determined. We have identified 5 categories of vitality class:

I - healthy individuals;
II - defoliated individuals;
III - severely defoliated individuals;
IV - withered individuals;
V - dead individuals.

The vitality structure of the tree layer was analyzed. The index of the vital state of the stand was also calculated using the formula (Eq. (1)):

$$I_n = \frac{n_1 + 0{,}7n_2 + 0{,}4n_3 + 0{,}1n_4}{n} \quad (1)$$

where I_n – life condition index;
n_1 – the number of individuals classified as "healthy";
n_2 – the number of individuals classified as "defoliated";
n_3 – the number of individuals classified as "severely defoliated";
n_4 – the number of individuals classified as "withered";
n – total number of individuals.

5. Results

Content of heavy metals in community components.

As can be assumed, with approaching the source of pollution, the amount of heavy metals in the components of the community is steadily increasing. However, the nature of this increase may vary depending on the specific component of the community (including its species) and the pollutant.

Organic soil horizons.

The content of nickel in the non-contaminated zone averages 7.5 mg/kg, copper - 16.75 mg/kg, cobalt - 1.5 mg/kg. In studies of past years, the value of 10 mg/kg for the first two metals is taken as background values. Consequently, a slight increase in the copper content is observed, which is most likely associated with the peculiarity of the location of the constant sample plot relative to the prevailing winds, as well as with the change in the activity of the plant (the use of various ores, the change in the nature of production and purification, etc.). We take the cobalt content as the background value.

In the buffer zone, the nickel content is about 50 mg/kg, which is 5 times higher than the background values. The content of copper ranges from 185.5 to 76.9 mg/kg (different sample plots), cobalt - from 2.72 to 5.63 mg/kg, which also significantly exceeds the background values.

In the impact zone, the concentration in all three cases sharply increases the concentration. For nickel, the content can reach 598.5 mg/kg (60 times), for copper - 3582 mg/kg (almost 360 times), for cobalt - 28.7 mg/kg (almost 20 times) (**Figure 4**).

The data obtained are consistent with the earlier stages of the study of this region. It should also be noted that this picture is observed with a decrease in the intensity of emissions into the atmosphere by the Severonikel plant. This indicates a strong fixation of heavy metals in the organic horizon and a very low rate of their leaching into the underlying horizons.

Community Component Characteristics.

Tree layer.

The main component of pine forests is a tree stand, the analysis of the vitality structure of which can indicate not only the state of the entire cenopopulation at the moment, but can also help to reveal the natural processes of formation and development, as well as reflect the effect of stress factors (in our case, this is aerotechnogenic pollution) To assess the vitality class, as a rule, a number of quantitative and qualitative signs are used. On the basis of these features, from 3 to 6 classes are distinguished and the vital state index is calculated (in our work we will limit ourselves to 5 classes).

In the non-contaminated zone (65 km and more from the source of pollution), healthy individuals of *Pinus sylvestris* L. dominate (from 61–68%). The ratio of defoliated individuals varies from 20–9%, those of severely defoliated ones - from 15–17%. The number of withered trees is minimal and ranges from 2–4%. Such a significant number of defoliated and severely defoliated trees can be explained by the competition between trees for water and nutrients in the soil, and further

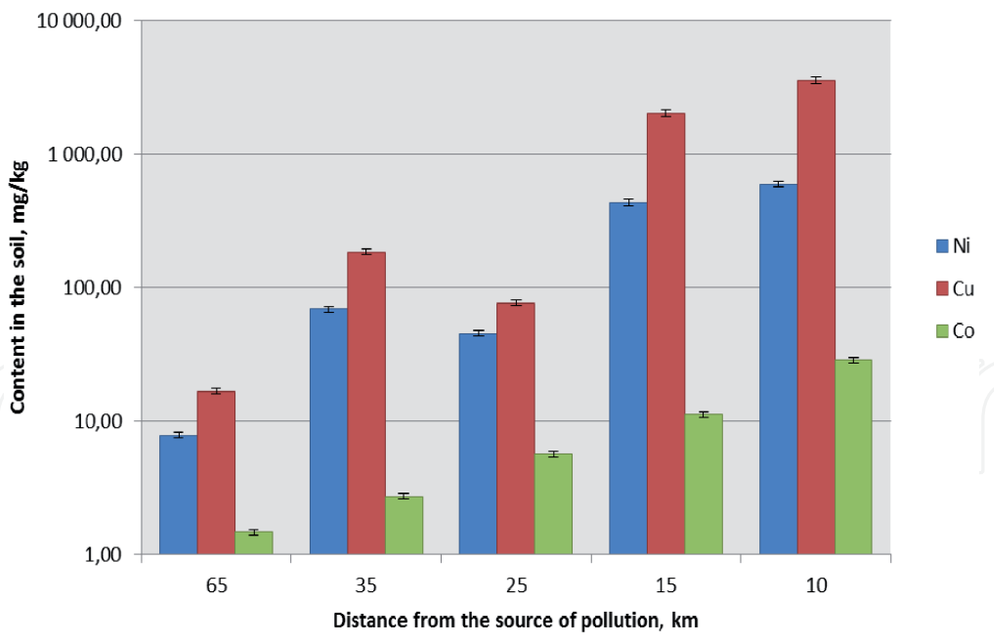

Figure 4.
The content of heavy metals in the organic soil horizon at different distances from the source of pollution (logarithmic scale of ordinates).

differentiation of populations of the same age by categories of vitality class. The vitality class index was 0.81.

In the buffer zone, the proportion of healthy plants does not exceed 64%. The share of defoliated and severely defoliated trees is 10% and 12%, respectively. These data are quite similar to what we observed in the non-contaminated regions. But at the same time, the share of withered trees is about 12%, which is significantly higher than the indicators of the non-contaminated zone. These data most likely indicate a decrease in the airborne anthropogenic load on forest communities (a large number of withered and dead trees indicates a higher level of pollution in the past). This is also confirmed by data from past years, which speaks of a significant suppression of the vital state. Thus, part of the trees with a decrease in the intensity of the aerial anthropogenic load passed into another group of vitality. The vitality class index is similar to that of the background areas and is 0.79.

In the vitality spectrum of the impact zone (15 km or less from the source of pollution), the situation changes dramatically. The proportion of healthy trees ranges from 10 to 25%. The proportion of defoliated individuals reaches 30%, and the proportion of severely defoliated ones - 45%. Moreover, the share of withered trees ranges from 8–32%. Here we see the predominance of weakened and strongly weakened individuals, which indicates a strong oppression of the entire community as a whole. And first of all, this is determined not only by the proximity to the source of pollution, but also by a change in the nature of the aerotechnological load (in the impact area, plants are affected not only by sulfur dioxide, but also by aerosol forms of heavy metals, which almost do not penetrate into the buffer zone). The vitality class index is 0.53 (**Figure 5**).

Ground tiers.

Assessment of the condition of the lower layers of boreal forests is no less important than assessing the condition of the tree layer. Moreover, here one of the most important criteria is the total projective cover.

In the non-contaminated zone, the total projective cover of the herb-dwarf shrub layer is about 20%. The dominant species are *V. vitis-idaea* L. and *V. myrtillus* L.,

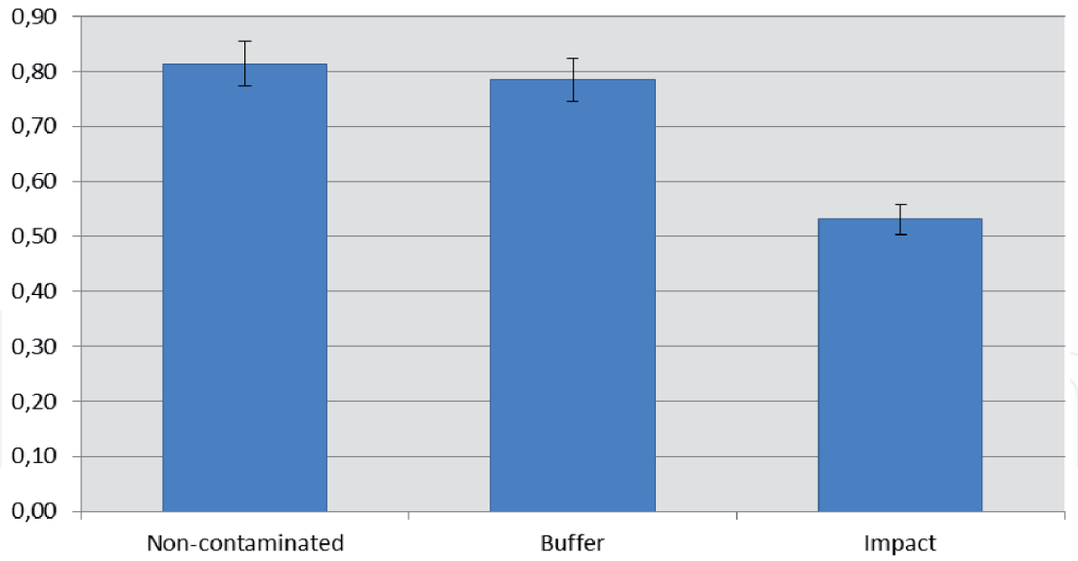

Figure 5.
Changes in the vital status index depending on the level of pollution.

occupying 9.5% and 12.5%, respectively. According to the data of previous studies, it can be done that the total projective cover of the herb-dwarf shrub layer gradually increases (on average, for the species of the genus *Vaccinium*, the total projective cover increased from 6% to fifteen%). First of all, this can be explained by the post-fire restoration of pine forests. And also a decrease in the intensity of emissions from the Severonikel plant (to a lesser extent).

The total projective cover of the moss-lichen layer is about 60% and is represented by lichens of the genus *Cladonia* (*C. stellaris* (Opiz.) Brodo, *C. rangiferina* (L.) Nyl., *C. mitis* (Sandst.) Hustich) and moss *Pleurosium shreberi* (Brid.) Mitt. It should be noted that the total projective cover of mosses is insignificant and amounts to no more than 1%. Such an insignificant amount of moss indicates a disturbance of the moss-lichen layer.

In the buffer zone, the total projective cover of the lower tiers begins to decrease, which indicates an increase in the airborne industrial load on the communities. The cover of the grass-dwarf shrub layer remains almost unchanged and amounts to 15-18%. In general, the herb-dwarf shrub layer of pine forests in the buffer and background regions does not differ significantly in terms of the total coverage and composition of dominant species.

The situation is different with the moss-lichen layer of the buffer zone. The total projective cover of the genus *Cladonia* decreases significantly and amounts to about 15%. At the same time, *Cladonia coccifera* (L.) Willd appears. - a species typical for successional communities. The total coverage of this type can be up to 30%. In this area, mosses are almost completely absent (hepatic mosses are occasionally found, but their effect on the total projective cover is insignificant).

Despite the reduction in the volume of emissions from the Severonikel plant, there is a noticeable deterioration in the lower tiers. Projective cover by *C. coccifera* (L.) Willd. increased almost 2 times. This is also evidenced by the almost complete absence of the species *P. shreberi* (Brit.) Mitt. In this case, it can be concluded that the moss-lichen layer is in a depressed state and is significantly disturbed.

In the impact zone, the total projective cover of the grass-dwarf shrub layer is on average about 5%. At the same time, the species composition changes sharply. *V. vitis-idaea* L. and *V. myrtillus* L. have a very depressed state. The number of *E. hermaphroditum* Hagerup increases, which becomes the dominant species and *Arctostaphylos uva-ursi* (L.) Spreng appears. This fact indicates a higher level of tolerance to

Figure 6.
Ground layer of pine forests in the non-contaminated (top left), buffer (top right) and impact (bottom) zones.

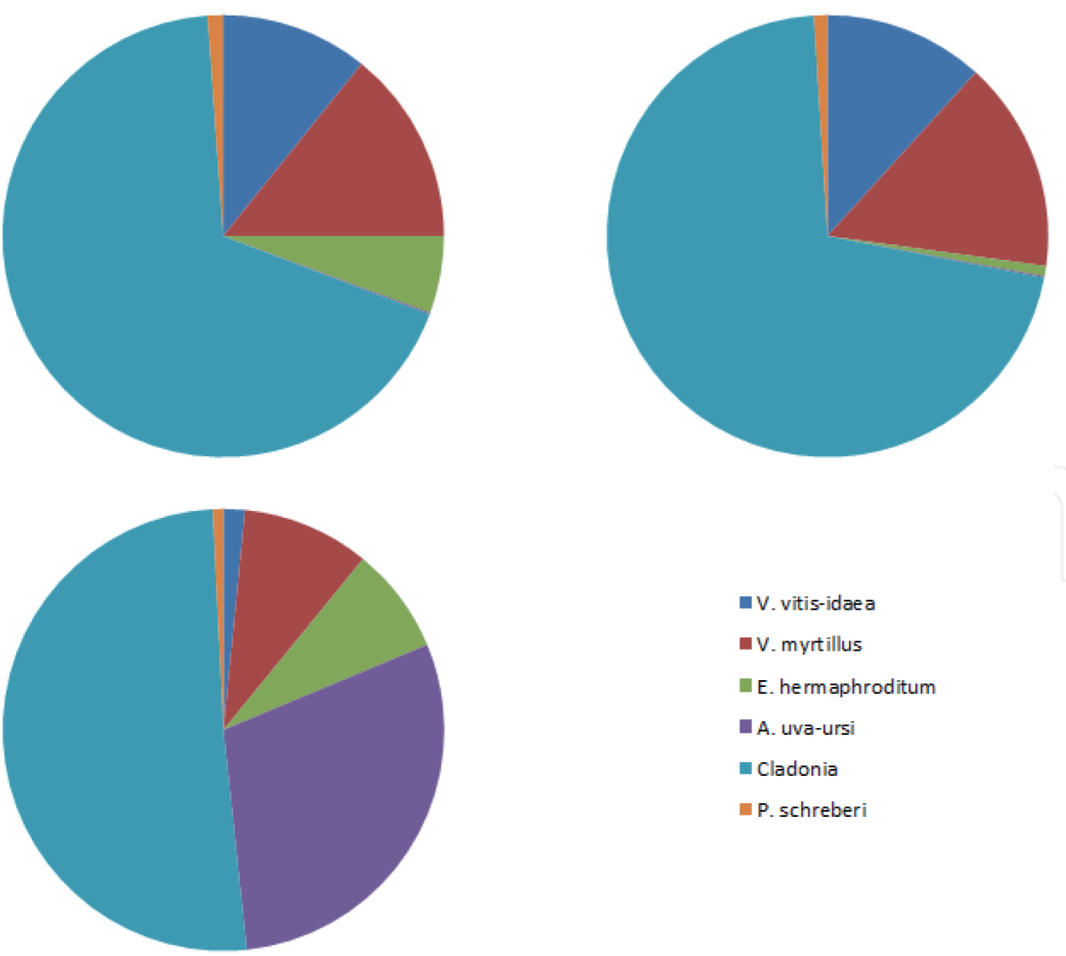

Figure 7.
Percentage ratio of species of the ground layer of pine forests in the non-contaminated (top left), buffer (top right) and impact (bottom) zones.

aerotechnogenic impact in these species compared to representatives of the genus *Vaccinium* (the projective cover is no more than 1.5%). This is also due to the destruction of the moss-lichen layer and litter, which play an essential role in maintaining the moisture capacity of organic soil horizons.

The total projective cover of the moss-lichen layer reaches 5%, which is significantly lower than in the buffer zone (in some cases, this indicator may be even lower). *C. coccifera* (L.) Willd becomes the dominant species. The lichens of the genus *Cladonia* disappear almost completely. Mosses are completely absent. Despite the decrease in the intensity of the airborne technogenic load, there was no significant change in the state of the lower tiers in the impact zone.

The study of the projective cover of ground layers can vary greatly depending on the distance to the source of airborne industrial pollution (**Figures 6** and 7).

6. Conclusions

The study made it possible to reveal some regularities in the effect of airborne pollution on the vitality structure of pine forests. First of all, our data are consistent with the results of other studies. General tendencies of the formation of forest communities under the conditions of aerotechnogenic load are revealed. The study showed that the vital state of the communities directly depends on the intensity and nature of the aerial anthropogenic impact.

Some features have also been identified. First of all, this concerns changes in the structure of communities in comparison with the data of previous years (there is a general trend towards an improvement in the living condition due to a decrease in emissions from the Severonikel plant). Based on the data obtained, it can be concluded that the pollution with sulfur dioxide and heavy metals is of a local nature.

The vitality structure of pine forests varies depending on the distance from the pollution source (and, accordingly, on the intensity of the aerial anthropogenic load). In the non-contaminated zone, the vitality index is 0.81; in the buffer zone - 0.79; in the impact zone - 0.53. Under the conditions of airborne industrial pollution, noticeable disturbances in the growth and development of the tree layer occur. There is a deviation from the monopodial type of branching (due to the death of the apical meristem of the leading shoot), a noticeable decrease in the increase in phytomass and a violation of the assimilation apparatus (the appearance of pronounced chlorosis and necrosis on the needles). The total projective cover and ground phytomass of the lower tiers noticeably decrease when approaching the pollution source. Moreover, in addition to the general oppression, there is a change in the dominant species in the synusia of the herb-dwarf shrub and moss-lichen layers.

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