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The Pathological Status of *Pinus sylvestris* L. Understory Affected by Anthropogenic Air Pollution Stress (Case Study of Forests near Krasnoyarsk)

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Abstract: Air pollution is the major anthropogenic factor in urban and industrial areas. Forests play the most important role in improving environmental quality in such areas. Long-term air pollution has an adverse effect on the entire biota in such forests and determines the nature of plant–pathogen interactions. The purpose of the present research was to study the pathological status of the understory in *Pinus sylvestris* L. stands subject to long-term anthropogenic air pollution. The study was conducted in the pine forests near Krasnoyarsk. Research methods included a detailed pathological inspection of the understory (including saplings and self-sown trees) in stands (mainly forest-steppe pine forests) growing from 10 to 30 km from the city and macroscopic and microscopic diagnostics of plant diseases, and the analysis of the data obtained was carried out using statistical criteria (Kolmogorov–Smirnov test ($d_{K\text{-}S}$), Student's *t*-test). Pathogens affecting young pines (nine species identified) are micromycetes of different parasitic strategies (semi-parasites predominate). The most common pathogens are *Lophodermella sulcigena* (causes needle cast), *Cenangium ferruginosum* (necrosis of branches), and *Sarea difformis* (stem and branches canker). The pathogens causing necrosis and canker are the most harmful for pine understory. As young plants mature, pathogen diversity and disease manifestations increase. In stands closer to the city, understory infestations with dominant diseases significantly decrease as the degree of their contamination with heavy metals and fluorine increases. The activity of pathogenic micromycetes is likely to be suppressed by the chemicals found in the plants.

Keywords: pine forests; understory; air pollution; plant pathogens; needle diseases; necrosis; canker; disease manifestation indicators; inhibition of phytopathogenic micromycetes

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1. Introduction

Human activities largely determine the current condition of forest ecosystems [1,2]. Pollutants derived from industrial areas and cities produce a damaging effect on surrounding forests, with these being essential to the health of our environment [3,4]. Increasing air pollution is one of the crucial factors disturbing forest ecosystems [5–7]. Industrial emissions affect forests in many regions of Russia and other countries [8–11]. To date, a large amount of scientific knowledge has been accumulated on the adverse effect of anthropogenic contaminants on forest ecosystems and their components (forest communities in particular).

Phytotoxic pollutants cause changes to tree species biochemistry and physiology [12–20]. As a response to anthropogenic stress, trees reduce their growing season length, duration of cambial activity [21], and annual radial increment combined with changes in wood anatomy [21–24]. Long-lasting air pollution leads to visible morphological damage to trees and shrubs (necrotic photosynthetic organs change color, tree crown degradation, habit shift, top dieback), root death [25–27], and affects plant reproductive systems [28–32]. Air pollution induces technogenic-digressive forest successions forming simple low-productivity forest ecosystems [33,34]. Scots pine (*Pinus sylvestris* L.) grows over a wide geographical range so its stands are often exposed to air pollution.

Air pollution, along with other anthropogenic factors, changes the composition of forest fungal and microbial communities, including pathogenic (potentially pathogenic) species and the nature of their relationship with woody vegetation [19,35,36]. Most research is focused on the air pollution impact on forests without considering their interaction with pathogens. Hence, this issue requires study. In forests subjected to industry-related stress, young woody plants accumulate high quantities of pollutants with these amplifying the negative effects of plant pathogens. These reasons and the importance of successful reforestation in maintaining sustainable forest ecosystems prompted us to research the topic.

The purpose of the present research was to study the pathology of young *Pinus sylvestris* L. subject to long-term air pollution (based on the example of pine forests near Krasnoyarsk). The research objectives included: identifying the dominant pathogenic consorts on the pine understory, determining the indicators of disease manifestations, and assessing the impact of anthropogenic air pollution on understory infestation with the primary mycoses.

2. Materials and Methods

2.1. Study Area and Study Objects

The study was carried out in *P. sylvestris* forests close to Krasnoyarsk, the largest urban ecosystem in Central Siberia (Figure 1). According to Korotkov's classification [37], our study was located in the forest-growing provinces of Kansk–Krasnoyarsk–Biryusa and East Sayan. Beryozovskiy Bor, Yesaul'skiy Bor, and Pogorel'skiy Borour belong to the forest-steppe zone of the Kansk–Krasnoyarsk–Biryusa forest-growing province. Pine forests of the Karaul'noe forestry of the Educational and Experimental Forestry of the Reshetnev Siberian State University of Science and Technology (Reshetnev University) belong to the subtaiga belt of the East Sayan forest-growing province. Table 1 shows the main silvicultural and forest inventory details from our studies. The research was focused on the study of *P. sylvestris* understory, its dominant pathogenic consorts, and the diseases they cause.

All the studied plantations have been subjected to recreational activities and air pollution for many years to varying degrees. The anthropogenic impact is most typical in forest-steppe pine forests. The level of pollution in pine forests is determined by the distance from the city and the prevailing winds. Beryozovskiy Bor (adjacent to the eastern outskirts of the city) has been facing long-term anthropogenic air pollution (the main sources are industrial enterprises, fuel and energy complexes, and roads). Yesaul'skiy Bor (located at a distance of about 30 km to the northeast of the city) is subjected to air pollution stress to a lesser extent (Figure 1). The main source of anthropogenic pollution in the Pogorel'skiy Bor stands (located at a distance of about 40 km to the north from the city) is road transport moving along the Yenisei tract [38].

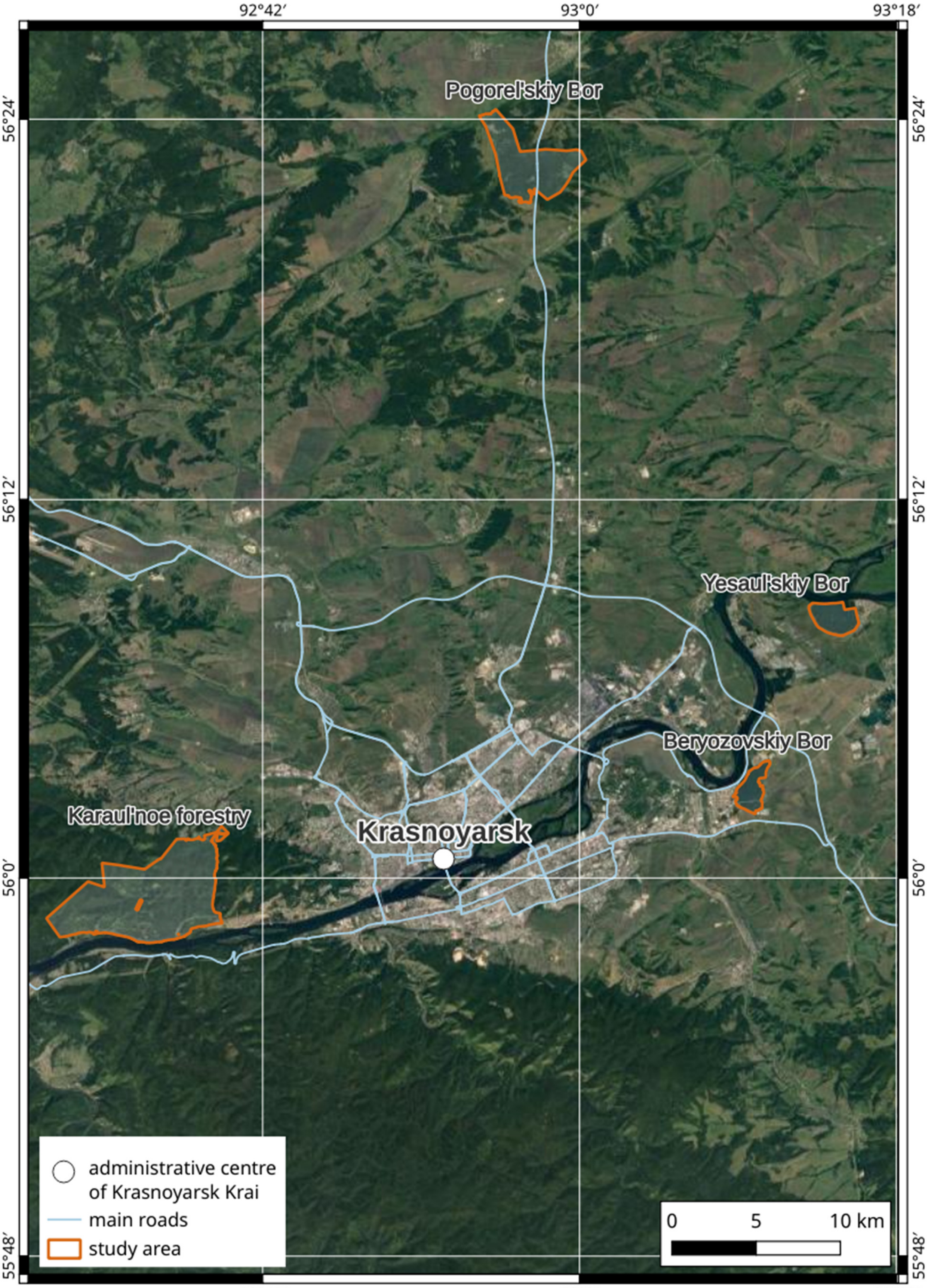

Figure 1. Study locations.

Table 1. Silvicultural and forest inventory of the studied forest stands. RP—research plot; P—pine; B—birch; 10P+B indicates that birch occupies 2.5–5.0% of the total growing stock on the research plot; 10P/ind.B indicates that birch occupies 0.1–2.4% of the total growing stock on the research plot.

Pine Forest	RP	Forest Stand Composition, Forest Type	Average Age, Years	Average Tree Height, m	Average Diameter, cm	Bonitet Class	Density
Karaul'noe forestry of the Educational and Experimental Forestry of the Reshetnev University	1	10P+B, herb-rich	110	27.5	30.9	2	0.8
	2	10P+B, eagle fern/herb-rich	110	24.0	37.4	3	0.7
	3	10P/ind.B, herb-rich	106	26.5	36.0	2	0.9
	4	9P1B, sedges/herb-rich	108	25.5	38.7	2	0.7
Beryozovskiy Bor	1	10P/ind.B, sedges/herb-rich	110	23.1	45.9	3	0.6
Yesaul'skiy Bor	1	10P, herb-rich/moss	110	19.7	33.2	4	0.7
	2	10P, herb-rich/moss	120	29.3	34.4	2	0.8
	3	10P, herb-rich/moss	120	26.0	38.0	2	0.8
Pogorel'skiy Bor	1	10P, sedges/herb-rich	110	25.5	28.4	2	0.8
	2	10P, sedges/herb-rich	117	26.5	32.0	2	1.0
	3	10P, sedges/herb-rich	110	26.1	27.6	2	0.9

2.2. Data Collection

We established rectangular temporary research plots in pine stands following the generally accepted method [39]: three research plots in each Yesaul'skiy Bor, Pogorel'skiy Bor, and Karaul'noe forestry, and one research plot in Beryozovskiy Bor. We examined the state of young trees and pathogens affecting them following the methods accepted in forestry and forest protection [40–42]. Twenty quadrats 2 m × 2 m were placed diagonally within each research plot. Wherever the understory was evenly distributed, the plots were placed at a distance of 5 m from each other. We avoided plots where the understory was scattered. A complete enumeration of pine understory (young trees older than 5 years) was carried out in the quadrants. Trees were divided into classes according to their condition (healthy or affected by diseases). In quadrats placed in Pogorel'skiy Bor we also studied the state of saplings (up to 2 years) and self-sown pine (2–5 years). Young plants with signs of disease in their needles were divided into four damage classes: 1—up to 25% of affected needles; 2—26–50%; 3—51–75%; 4—over 75%. If the understory was affected by canker, we identified three classes of tree damage: 1 (weak damage)—no cankers on stems; cankers on shoots and branches, often sealed with tar; 2 (medium)—sporadic cankers on stems; 3 (severe)—a lot of cankers on stems.

Reference literature and guides [43–46] were used to diagnose infectious diseases in the understory, including self-sown trees and saplings, by identifying a set of symptoms: specific anatomical and morphological disorders in plant parts, and vegetative and reproductive formations of pathogens. When in doubt, we photographed affected objects (at least 15 images) for additional diagnosis of diseases and identification of pathogens. We also collected needle samples (at least 15) to identify diseases. Collected samples went through pathographic and microscopic analysis for additional diagnostics of diseases. Current names of phytopathogenic fungi are given in accordance with the CABI publication Index Fungorum [47].

We used the following indicators to determine anthropogenic air pollution stress in pine forests: fluorine and heavy metals accumulation in needles (both on the surface and in the tissues); and water-soluble fluorine compounds content in the content of forest soil. The measurements were carried out on research plots located in the central part of each of the forest-steppe pine forest stands. Along the perimeter of each research plot, needle samples were taken from five model trees. Samples were taken from pine understory in a similar way.

Soil sampling was carried out in autumn since it is the period of maximum fluorine accumulation. Samples were taken at depths of 0–5, 5–10, and 10–20 cm in five places on the research plot (in the center and at the four corners). Then, in the laboratory, a mixed sample was prepared and air-dried.

The pollution indicators including phytotoxic microelements' (lead, zinc, vanadium, chromium, fluorine) contents in needles and on their surface, and water-soluble fluorine compounds content in forest soil were identified using standardized chemical methods [48] at the Center of Agrochemical Service "Krasnoyarskiy".

2.3. Material Analysis

Based on the materials provided by a detailed plant pathology diagnosis of the understory, we identified the existence of two main indicators of the dominant plant diseases on each research plot: prevalence and growth infection rate. The prevalence of a disease (infection of young plants within a research plot) was calculated as:

$$P = \frac{n}{N} \times 100, \quad (1)$$

where P is the prevalence, %; n is the number of sick plants; and N is the total number of registered plants.

The understory infection rate (R) was calculated using the formula:

$$R = \frac{\Sigma(nb)}{NK} \times 100, \quad (2)$$

where R is the growth infection rate, %, $\Sigma(nb)$ is the sum of the product of the number of sick plants (n) multiplied by the damage class value as accepted in *Data Collection* section (b), N is the total number of registered plants, pcs., and K is value corresponding to the highest damage class as accepted in *Data Collection* section (3—for canker diseases, or 4—for needle diseases).

Similar indicators were calculated for diseases of self-sown trees and saplings in the Pogorel'skiy Bor pine forest.

Data (samples) processing and analysis were carried out using statistical methods. We used the Kolmogorov–Smirnov test ($d_{K\text{-}S}$) to check if analyzed samples were normally distributed. Student's t-test was used to conduct a comparative analysis of the average indicators of the manifestation of the dominant diseases in the understory (P—prevalence, R—growth infection rate) according to detailed records in forests with different degrees of anthropogenic pollution. The accepted level of significance was $p \leq 0.05$. Statistical calculations were performed using STATISTICA 10 software

3. Results

We identified a complex of pathogens and diseases affecting the understory (saplings and self-sown trees) in the studied pine stands. The dominant pathogens were represented by micromycetes at different levels of parasitic activity infecting the aerial parts of plants (Table 2). Indicators of manifestation levels are shown in Table 3.

Infectious diseases of young tress in the studied pine forests occurred on plants of different ages—saplings, self-sown trees, and understory (Table 4). At the same time, diseases and their symptoms have certain dynamics in the ontogeny of young pine trees.

The levels of air pollution of the main components of the forest-steppe pine forests decreased with the distance between pine stands and the city, and were consistent with prevailing winds (W→E) (Table 5).

Additional infographics clearly demonstrate the change in air pollution stress affecting the understory in forest-steppe pine forests as the distance from the city decreases (Figure 2). The same is correct for the mean values of quantitative indicators of the manifestation of dominant mycoses in the understory (Figure 3). Understory inspections were also conducted on sample plots placed in comparable stands in the central parts of three forest-steppe pine forest understories. Table 6 shows the results of a comparative analysis of diseases in understory in pine forests with different degrees of air pollution.

Table 2. Infectious diseases of *P. sylvestris* understory (saplings and self-sown pine).

Pathogen	Parasitic Strategy	Disease
Lophodermium pinastri (Schrad.) Chevall.; *L. seditiosum* Minter, Staley and Millar	Facultative parasite	*Lophodermium* needle cast
Gremmenia infestans (P. Karst.) Crous (=*Phacidium infestans* P. Karst.)	Facultative parasite	Snow blight
Lophodermella sulcigena (Link) Höhn.	Facultative parasite	*Lophodermella* needle cast
Coleosporium sp.	Obligate parasite	*Coleosporium* rust
Cyclaneusma minus (Butin) DiCosmo, Peredo and Minter (=*Naemocyclus minor* Butin.)	Facultative parasite	*Cyclaneusma* needle cast
Cenangium ferruginosum Fr.		*Cenangium* canker
Thyronectria cucurbitula (Tode) Jaklitsch and Voglmayr (=*Nectria cucurbitula* (Tode) Fr.)	Facultative parasite	*Nectria* canker
Sarea difformis (Fr.) Fr. (=*Biatorella difformis* (Fr.) Vain.)	Facultative parasite	*Biatorella* canker
Cronartium pini (Willd.) Jørst. (obligate parasites)	Obligate parasites	Scots pine blister rust

Table 3. Manifestation indicators of the understory diseases (mean values with standard error): numerator—prevalence, %; denominator—growth infection rate, % (for all samples: n = 20, $d_{K\text{-}S}$ $p > 0.05$); RP—research plot; sp.—sporadically (meaning, occurring in individual trees only).

Pine Forest	RP	*Lophodermium* Needle Cast	Snow Blight	*Lophodermella* Needle Cast	*Coleosporium* Rust	*Cyclaneusma* Needle Cast	*Cenangium* Canker *	*Nectria* Canker	Scots Pine Blister Rust	*Biatorella* Canker
Karaul'noe forestry of the Educational and Experimental Forestry of the Reshetnev University	1	sp.	4.6 ± 1.7 / 35.7 ± 3.3	27.6 ± 3.7 / 9.0 ± 1.5	sp.	-	44.7 ± 2.7 / 20.5 ± 1.8	-	sp.	22.5 ± 2.1 / 10.4 ± 2.1
	2	-	5.2 ± 1.9 / 35.2 ± 2.8	46.3 ± 5.2 / 14.6 ± 1.5	-	-	26.3 ± 3.0 / 12.3 ± 1.8	-	-	19.1 ± 3.4 / 11.6 ± 1.9
	3	-	2.9 ± 1.3 / 30.1 ± 2.4	17.7 ± 4.1 / 5.1 ± 1.3	-	-	34.1 ± 2.4 / 16.7 ± 1.7	sp.	sp.	41.7 ± 3.8 / 31.8 ± 3.1
	4	sp.	4.0 ± 1.5 / 41.3 ± 3.6	28.2 ± 3.2 / 7.7 ± 1.0	-	-	26.3 ± 3.2 / 10.5 ± 1.6	-	-	38.0 ± 2.2 / 22.5 ± 2.0
Beryozovskiy Bor	1	38.8 ± 4.1 / 9.7 ± 1.5	-	28.2 ± 2.4 / 7.4 ± 0.7	-	-	11.0 ± 2.1 / 4.3 ± 1.0	-	-	9.1 ± 0.9 / 5.9 ± 0.7
Yesaul'skiy Bor	1	2.8 ± 1.1 / 1.2 ± 0.3	-	43.8 ± 6.1 / 15.0 ± 1.7	-	-	72.4 ± 5.1 / 48.8 ± 3.1	-	-	66.7 ± 4.5 / 36.2 ± 2.8
	2	13.4 ± 2.0 / 3.4 ± 0.9	-	29.5 ± 3.3 / 7.4 ± 1.1	-	-	30.2 ± 2.3 / 24.8 ± 1.9	sp.	-	14.8 ± 1.6 / 7.4 ± 1.9
	3	11.6 ± 1.8 / 3.6 ± 1.0	-	50.0 ± 3.9 / 13.3 ± 1.3	-	-	59.6 ± 4.9 / 34.5 ± 3.5	-	-	48.5 ± 3.6 / 23.9 ± 2.3
Pogorel'skiy Bor	1	7.0 ± 1.3 / 3.0 ± 0.9	-	74.0 ± 3.9 / 31.8 ± 2.5	-	sp.	63.0 ± 4.3 / 31.0 ± 2.8	-	-	50.0 ± 3.3 / 39.0 ± 2.6
	2	6.6 ± 1.2 / 1.8 ± 0.2	sp.	71.3 ± 4.0 / 27.9 ± 2.6	sp.	sp.	50.8 ± 3.7 / 30.7 ± 3.0	-	-	54.9 ± 1.9 / 44.3 ± 3.2
	3	5.8 ± 1.3 / 1.4 ± 0.1	-	88.3 ± 5.0 / 39.1 ± 2.7	sp.	sp.	35.0 ± 2.4 / 16.7 ± 1.9	-	-	46.6 ± 3.0 / 37.9 ± 2.4

* In combination with necrosis of unknown etiology.

Table 4. Prevalence (numerator) and growth infection rate (denominator) of diseases in young pine trees in relation to age classes, % (Pogorel'skiy Bor data); sp.—sporadically (meaning, occurring in individual trees only).

Disease	Age Class		
	Saplings (up to 2 Years)	Self-Sown Pine (2–5 Years)	Understory (over 5 Years Old)
Lophodermella needle cast	21.0 ± 1.9 / 5.0 ± 1.5	55.2 ± 4.2 / 17.3 ± 1.9	77.9 ± 4.9 / 32.9 ± 3.2
Lophodermium needle cast	7.1 ± 1.0 / 2.2 ± 0.7	28.6 ± 3.2 / 9.4 ± 1.3	6.5 ± 1.3 / 2.1 ± 0.7
Snow blight	-	sp.	sp.
Coleosporium rust	-	-	sp.
Cyclaneusma needle cast	-	sp.	sp.
Cenangium canker	-	1.8 ± 0.2 / 1.4 ± 0.1	49.6 ± 3.5 / 26.1 ± 2.4
Biatorella canker	-	sp.	50.5 ± 3.7 / 40.4 ± 2.5

Table 5. Indicators of air pollution in pine forests.

Indicator	Beryozovskiy Bor (10 km East)	Yesaul'skiy Bor (about 30 km North-East)	Pogorel'skiy Bor (about 40 km North)
Microelements' contents on the surface of needles, mg/m^2	29.7 [1]/41.1 [2]	27.9/38.4	4.5/31.2
incl. fluorine	4.0 [1]/13.2 [2]	2.4/9.6	-/-
Microelements' contents in needles, mg/kg dry weight	25.4 [2]	6.5	4.2
incl. fluorine	20.0 [2]	2.0	-
water-soluble fluorine compounds content in forest soil, mg/kg	25.0 [2]	21.0	1.6

[1] trees; [2] understory.

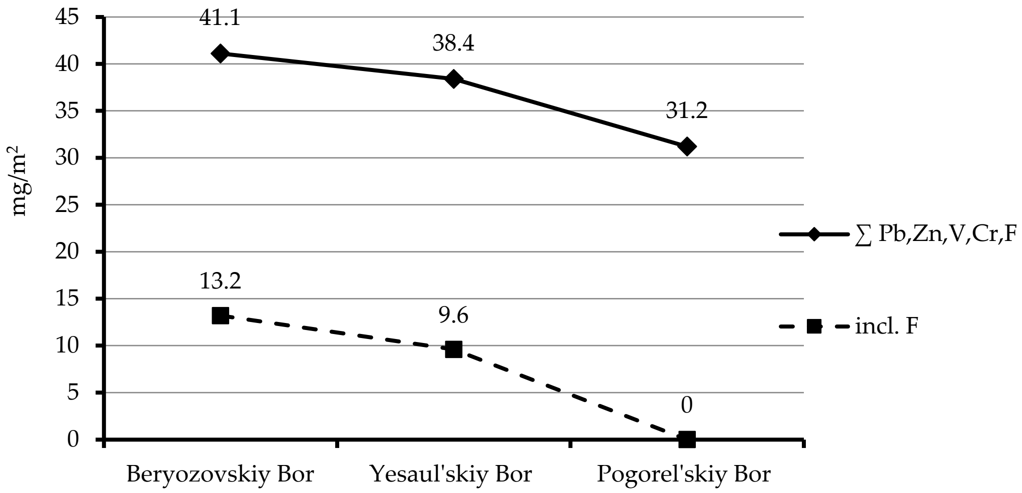

Figure 2. Phytotoxic microelements' (lead, zinc, vanadium, chromium, fluorine) contents in needles of pine understory outside Krasnoyarsk.

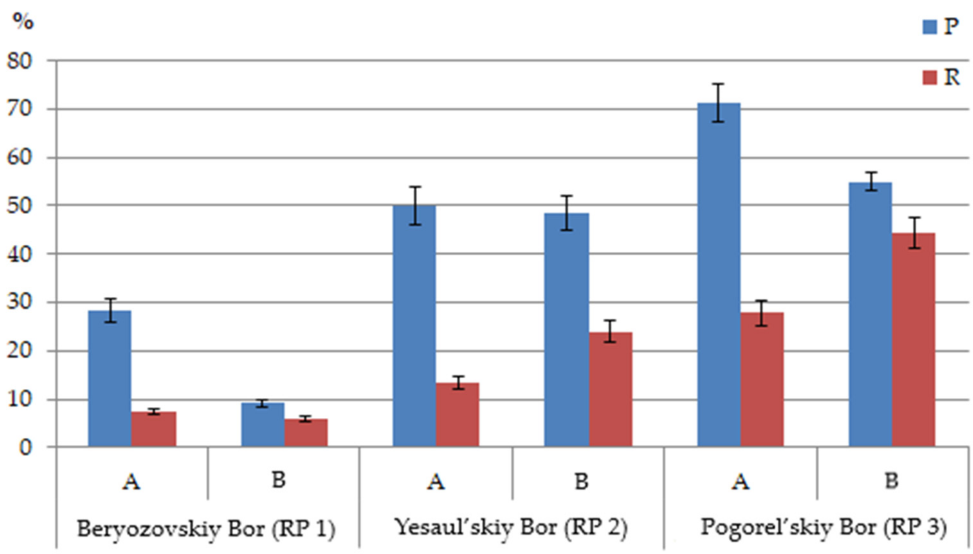

Figure 3. Manifestation indicators (*P*—prevalence, *R*—growth infection rate) of understory diseases: A—*Lophodermella* needle cast (pathogen—*Lophodermella sulcigena*); B—*Biatorella* canker (pathogen—*Sarea difformis*); RP—research plot. Error bars represent standard error.

Table 6. Comparative analysis of dominant understory diseases in pine stands with different degrees of air pollution (based on the Figure 3 data).

Understory Diseases	Manifestation Indicators	Compared Samples, n = 20 (t_{05} = 2.1)	
		Beryozovskiy Bor—Yesaul'skiy Bor	Yesaul'skiy Bor—Pogorel'skiy Bor
Lophodermella needle cast	P	t_{true} (4.8) > t_{05}	t_{true} (3.5) > t_{05}
	R	t_{true} (4.4) > t_{05}	t_{true} (4.4) > t_{05}
Biatorella canker	P	t_{true} (10.7) > t_{05}	t_{true} (1.5) < t_{05}
	R	t_{true} (7.2) > t_{05}	t_{true} (5.4) > t_{05}

P—prevalence; *R*—growth infection rate.

4. Discussion

Pathogens affecting young *P. sylvestris* in forest near cities included micromycetes that infected needles causing necrosis and canker in branches and stems (Table 2). The predominant pathogens were mostly semi-parasites (facultative parasites, facultative saprotrophs), so infection accumulated on shrunken parts of plants and coniferous needle litter. A greater variety of diseases (hence, pathogens) occurred in the subtaiga pine forests (Karaul'noe forestry), which was probably due to the heterogeneity of biotopes in these forests and their lesser anthropogenic transformation in comparison with forest-steppe biogeocenoses.

Diseases affecting needles prevailed, making up 56% of the pathocomplex. Most of the diseases in this group did not cause noticeable symptoms. *Lophodermium* needle cast (pathogens—*Lophodermium* sp.) was found on young plants, mainly in the forest-steppe; the damage of individual juvenile needles did not pose a threat to plants. The prevalence of snow blight rarely exceeded 5% (Table 3), although it could lead to critical defoliation and the fatal weakening of individual plants in understory populations. The disease occurred mainly in subtaiga pine forests, where a deep snowpack and its later melting in spring provided optimal hydrothermal conditions for the under-snow development of the pathogen (*Gremmenia infestans*).

We observed *Cyclaneusma* needle cast and *Coleosporium* rust, detected at the beginning of the growing season by aecia growing on needles on individual plants. *Cyclaneusma* needle cast (pathogen—ascomycetous fungus *Cyclaneusma* minus), which we identified on self-sown trees and young understory in Pogorel'skiy Bor, is one of the little-studied diseases of conifers in Central Siberia [46,49]. The main diagnostic symptoms of this mycosis were: the entire needle became yellow and then brown, and most importantly, the formation of yellow flat ascomata (apothecia) up to 0.5 mm long, pushing through the needle epidermis.

Among the diseases of the phyllosphere, *Lophodermella* needle cast was characterized by a high level of manifestation (Table 3). However, even with a large number of needles affected by the disease, a significant area of their surface continued to produce, since the upper parts of the needles usually die off. Pathological defoliation occurred only in cases of their critical damage and dieback.

Quantitative indicators of diseases proved that the most harmful pathogens were those affecting woody tissues and causing necrosis (in particular, *Cenangium* canker) and *Biatorella* canker (Table 3). These diseases affected weakened understory growing under excessive shading. Insect borers, branches, and stem injuries contributed to infection and the growth infection rate increases.

Nectria canker and Scots pine blister rust were not common in the understory. Scots pine blister rust, found in individual young trees in subtaiga pine forests, caused their rapid dieback.

Pathogen biodiversity and the indicators of the disease manifestations correlated with the age of the younger generation plants. On saplings, only diseases of needles (*Lophodermella* needle cast and *Lophodermium* needle cast) were observed (Table 4). The variety and manifestations of diseases increased in self-sown pines (2–5 years) infected with pathogens damaging woody tissues and causing necrosis and canker. However, the prevalence of such pathogens on self-sown trees was insignificant. For example, *Cenangium* canker was observed in individual trees only, and the *Biatorella* canker incidence rate did not exceed 2%.

We observed a whole range of identified diseases in the understory (young plants over 5 years old). The pathogens often develop on plants together in certain combinations, causing complex damage. The indicators of disease manifestation in such plants reached maximum values, making a significant part of the understory (more than 50%) fall into the category of drying out.

In forests exposed to anthropogenic stress, the colonization and activity of pathogens and the harmfulness of the diseases depended on the long-term air pollution. The understory was most susceptible to air pollution [19]. Table 4 shows that the above-mentioned statement applies particularly to the understory. In the studied pine forests, the degree of contamination of needles with biologically active and highly toxic compounds of lead, zinc, vanadium, molybdenum, chromium, and fluorine was 1.4–7 times (a) higher in the understory than in the crowns of the canopy. Pollutants settled out due to the action of gravity and entered into the understory with precipitation. Chemicals from numerous motor vehicle emission also entered directly into the understory. Plant contamination with phytotoxic microelements and the accumulation of their water-soluble compounds in needle tissues was noticeably higher in Beryozovskiy Bor compared to Yesaul'skiy Bor and, even more so, Pogorel'skiy Bor (Table 5, Figure 2). In Pogorel'skiy Bor, located at a considerable distance to the north of the city (with prevailing westerly winds), plant contamination with the most toxic fluorine compounds was unrecorded.

A comparison of the infographics for the studied forest-steppe pine forests (Figures 2 and 3), which differed in their air pollution stress levels, shows a trend towards an increase in the prevalence and growth infection rate in the understory along the gradient of decreasing air pollution with the most phytotoxic microelements, including fluorine. Table 5 shows that the trend was confirmed by a *t*-test used to determine the significance of differences. Industrial emissions not only caused surface contamination in young plants, but also accumulated in bark and needles [50], suppressing the parasitic activity of pathogens and growth infection rate in the pine understory. Chemical pollution had an adverse effect on the vegetative organs and the reproduction of micromycetes. The accumulation of pollutants on the surface of plants prevented their infection [51–54].

The accumulation of mycotoxins in the snow was one of the possible factors limiting snow blight infestations in the understory in the most polluted forest-steppe pine forests (Beryozovskiy Bor and Yesaul'skiy Bor). The pathogen (*G. infestans*) was vulnerable when developing under the snow, forming exophytic mycelium and maturating and opening fruiting bodies (apothecium) during the Siberian-type disease cycle [54].

5. Conclusions

The young generation of forest-forming species (saplings, self-sown trees, and understory trees) is a very important component of forest ecosystems. The number and vital status of young plants determine the potential for natural forest regeneration. The condition of the forest understory near urban conglomerations is influenced by many factors, including plant pathogens, recreational loads and air pollution. According to the data obtained in the forest-steppe pine forests growing near Krasnoyarsk, the contamination with heavy metal and fluorine compounds was 1.4–7 times higher in the understory than in the canopy, and anthropogenic air pollution decreased with the distance from the city.

Pathogens affecting young *P. sylvestris* trees are micromycetes which have different strategies (semiparasites predominate) for damaging the aboveground parts (needles, branches, and stems). Of the identified phytopathogenic micromycetes (nine species), the most common were *Lophodermella sulcigena* (affecting the upper parts of the needles), *Cenangium ferruginosum* (causing the necrosis of branches), *Sarea difformis* (causing canker on stems and branches). The most harmful pathogens for the pine understory are those causing necrosis and canker since they lead to the partial or complete dieback of plants.

When young plants grow up (saplings → self-sown trees → understory), the diversity and incidences of disease manifestations increase.

Understory damage by dominant diseases (their prevalence and growth infection rate) in pine forests near cities significantly decreases near the urban area as the degree of air pollution increases (it was determined for *Lophodermella* needle cast and *Biatorella* canker caused by *L. sulcigena* and *S. difformis*, respectively). A number of chemicals (heavy metals and fluorine) accumulated in plant tissues pose fungistatic and fungicidal actions inhibiting the development of pathogens.

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