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Pine needles and soil as bioindicators of forest ecosystems in the anthropogenically disturbed *areas of the Baikal region*

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Abstract. Forest ecosystems of Baikal region were chosen a subject of comprehensive research conducted on the basis of the monitoring network created. Recommendations of the international manual ICP Forests, as well as the authors' developments were used for the research. The study was focused on toxicological, physiological-biochemical, and biogeochemical indicators that adequately reflect the state and manifestation of the protective properties of the forest ecosystem main components (tree-stand and soil) under the influence of anthropogenic factors – air pollution, urbanization, and irrational forest management. The assessment of the vital state of tree-stands of Scots pine (indicator species) was carried out on the basis of representative indicators: pigments, the level of enzymatic and non-enzymatic components of antioxidant protection, the content and ratio of biogenic elements, changes in morphometric parameters. When studying soil in anthropogenically disturbed territories, an increase in soil density, a decrease in natural moisture, aeration, and humus content were found, alkalization of the upper horizons and accumulation of pollutants with a low migration rate in the upper horizons of the soil profile. Air pollution and high recreational load were shown to produce the greatest stressful impact on the forest ecosystems.

1 Introduction

The role of forests as stabilizers of the natural environment is hard to overestimate. Being one of the most important parts of the biosphere, they perform climate-regulating, water-regulating, anti-erosion, sanitary-hygienic, recreational and other environmentally significant functions, many of which do not have cost indicators, but are often not less, but much more important than wood resources [1, 2]. At the same time, sustainable functioning of forest ecosystems and their full implementation of ecosystem functions/ services is possible only in the conditions of natural undisturbed state of the whole diversity of its components (plant communities, soil cover, fauna, microorganisms) that provides the current climate, hydrothermal, and other natural biogeochemical processes in a certain area [3]. However, according to the State of the World's Forests Report [4], deforestation and forest degradation

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continue at an alarming rate, with a significant impact on the ongoing loss of biodiversity. In this regard, studies aimed at identifying problem areas where the pressure of negative factors that suppress protective and compensatory mechanisms of organisms, populations, and cenoses and cause the development of pathological processes resulting in ecosystem degradation is particularly urgent [5, 6, 7]. Such territories are the first to be addressed while developing and implementing scientifically based measures to restore disturbed forest biogeocenoses and introduce effective methods for monitoring their condition [8]. As for the Baikal region, despite its recognized unique status, in the modern period its natural complexes are under exceedingly increasing pressure of anthropogenic factors that disturb composition, structure and functions of ecosystems, including forest ecosystems [9]. Urgent scientifically substantiated measures are required to optimize the use and restoration of the disturbed natural landscapes of the region. Our research is aimed at obtaining up-to-date information on the state of the forests as one of the main environmental and water protection components in this area.

Researchers recognize that the state of forests is a highly informative integral indicator that adequately reflects the unfavorable environmental situation caused by the impact of natural and anthropogenic factors, including climate changes, technogenesis, recreational load [10]. Moreover, the assessment of the forests state has an important social significance as a necessary aspect of human habitat indication. The results of such an assessment should be taken into account when taking decisions on the location of industrial enterprises, new settlements and recreation areas, as well as when creating specially protected areas. Among the effective monitoring methods that allow to determine with the greatest confidence the degree of negative impact on the forest ecosystem, advantageous are, in our opinion, the methods that assess the change in the state of its main components – the tree layer (tree-stand) and the soil [9]. Measurement of a number of representative parameters of these components yields present-day information about the degree of their oppression, the rate of development of the pathological process, and the activity of protective reactions. The approach we elaborated ensures a comprehensive and systemic study of the state of forest biogeocenosis. The obtained results are necessary for the subsequent assessment of different ecosystem services (supporting, regulating and other) of forests in the region. According to the literature, many studies are based on forest monitoring using one or more different parameters that characterize a particular component of the ecosystem, often without substantiating the ecological interdependence of these parameters. Chemical composition and biochemical changes in needles [11], some parameters of chlorophyll fluorescence [12], accumulation of heavy metals in ecosystems [13, 14], and other indicators can be used for monitoring. The non-systemic approach, in our opinion, does not provide complete information about the state of biogeocenosis as a whole, about disturbance of functional relationships between phytocenosis and soil, about the adaptive properties of producers (primarily woody plants) and the buffer capacity of the soil under the long-term impact of anthropogenic factors.

The purpose of this work is to study the pine forests of the Baikal region on the basis of the bioindicators (tree-stands and soil) under the influence of anthropogenic factors – technogenic air pollution, urbanization and irrational forest management.

2 Materials and Methods

The research was carried out on the territory of the Baikal region. The territory studied is characterized by mountain hollow rugged relief, highly continental climate, low average annual precipitation, low annual sum of positive temperatures and wide amplitude of their fluctuations, short plant vegetation period, and, consequently, low atmospheric ability for self-cleaning. A monitoring network was created, including about 200 sample plots (SP). SP were arranged in the tree stands, similar by grow class and age, according to commonly accepted and comprehensively described methods in publications [15, 16], with relief peculiarities, regional wind regime, and local circulation of air masses considered. The region is dominated by larch and pine forests. The Scots pine (Pinus sylvestris L.) was chosen as an indicator species. In the region, mixed-grass pine forests are common, mainly of the III class of bonitet. The main type of soil is gray forest. The soil profile is usually represented by a set of horizons: AO – A1 – A2 – A2B – B1 – B2 – BC – C. SPs were laid in the background (undisturbed) forest areas and in woodlands affected by anthropogenic factors – near cities, highways, large industrial enterprises, as well as tourist areas with a particularly high recreational load (from 500 thousand to 800 thousand people per year), causing recreational digression of forests.

Samples of pine needles and soil were taken at each SP, and a wide range of indicative parameters were determined, including the following: the content of photosynthetic pigments, enzymatic and non-enzymatic components of antioxidant protection, the content and ratio of biogenic elements. The content of pigments (chlorophylls a, b and carotenoids), hydrogen peroxide, free proline, ascorbic acid, flavonoids, glutathionethe, total activity of peroxidase were determined using a spectrophotometric methods, biogenic elements by atomic adsorption method [17], changes in the morphostructural parameters of needles and shoots. The state of the soil was assessed by the degree of the destruction of the forest litter, this component of the soil cover is very important for the forest ecosystem functioning [18]. Physical parameters and acidity of the upper soil horizons, the content of biogenic elements in the soil absorbing complex (SAC) were also determined. In technogenically polluted areas, the content of a number of pollutants (sulfur, fluorine, heavy metals) was also determined in pine needles and soil, and the total coefficients of their concentration (Zc) were calculated. According to Zc, the levels of low, middle, heavy and critical pollution were distinguished. Devices and equipment of the Collective Use Centers – the Baikal Analytical Center in the Irkutsk Scientific Center SB RAS and the Center "Bioanalytics" in the SIFIBR SB RAS – were used for the research. The data were statistically processed using the MS Excel 2010 application software package and the "Statistical Computing Environment R". The assurance of the data differences was evaluated by the nonparametric Mann-Whitney test (at $P \leq 0.05$).

3 Results and Discussion

There was revealed a marked decrease in the morphostructural parameters of pine trees in the territories affected by various anthropogenic factors, with the level of crown defoliation increasing sharply in comparison with the background values (Tab. 1). For example, under the influence of technogenic emissions, this indicator increases by 2.5–3 times, in urban territories and large under tourist’s flows – by 2–2.5 times.

Table 1. Morphostructural parameters of pine trees in background areas and in the disturbance areas.

Factors of forest disturbance	Shoot length, cm	Shoot needle mass, g	Needle length, mm	One needle mass, mg	Tree trunk volume, m^3	Crown defoliation, %
Technogenic emissions	9.4±1.2	3.7±1.1	49.9±3.6	25.8±4.7	0.41±0.1	45 – 70
Urbanization	12.5±1.4	4.2±1.0	55.5±3.5	28.8±8.6	0.44±0.1	40 – 55
Large tourists flows	8.2±2.6	3.5±0.9	45.7±5.4	28.3±2.1	0.38±0.1	40 – 60
Background areas	17.8±1.7	6.8±1.3	66.8±5.7	37.7±6.5	0.89±0.1	20 – 25

A strong compaction of the upper humus horizons of the soil is detected, with a significant increase in density, porosity, humidity and aeration decrease, pH shifts to alkaline side (Tab. 2). At the same time, it was found that a number of parameters in territories with large tourist flows, that is, with a large recreational load on the soil, are reduced to the greater extent than in urbanized the territories and even in some cases in technogenically polluted areas. Studies show that with an increase in tourist load, the thickness of the forest litter decreases by 5 times, the density of soils increases by 1.8–2 times, the content of natural moisture by 2–2.2 times, porosity and aeration by 3.1–3.3 times.

Table 2. Physical and chemical parameters of the upper horizons (0–20 cm) of forest soils in background areas and in the disturbance areas.

Factors of forest disturbance	Capacity of forest litter, cm	Bulk density, g/cm^3	Soil moisture content, %	Aeration, %	$pH_{(water)}$	Humification, %
Technogenic emissions	1.0-3.0	1.2±0.3	34.2±3.2	29.5±3.4	8.1±1.1	20-35
Urbanization	0.7-2.0	1.3±0.4	28.3±2.7	15.9±2.2	7.8±0.8	15-25
Large tourists flows	0.5-1.5	1.4±0.4	22.5±2.3	12.5±2.7	7.6±1.1	10-15
Background areas	2.5-7.5	0.7±0.1	48.4±4.2	40.7±3.6	5.3±0.6	50-65

The decomposition of organic matter, in particular, humus, slows down in all anthropogenically disturbed territories, it leads to a decrease in the proportion of humic acids. These pathological processes cause a disturbance in the soil nutrient regime, and consequently, the mineral nutrition of plants. In the forests adjacent to tourist areas, disturbances of edaphic conditions are more pronounced. This is evidenced by a decrease in the humus content by 5-6.5 times compared with the background values. Thus, active recreational digression is a powerful, albeit local, factor of forest disturbance in the region, and it should be strictly regulated.

As for the impact on forests of another strong negative factor – industrial emissions, it is manifested in much larger areas. At the same time, technogenic emissions affect tree-stands and the biogeocenosis as a whole not only indirectly, distorting the biogeochemical cycles of many elements, but also directly. Accumulation of pollutants in the assimilation organs of plants leads to disturbance, first of all, of the activity of photosynthesis, an imbalance in the elemental composition, which at the organism level is manifested in changes in the growth characteristics of trees [9, 19]. In the region, the chronic influence of industrial emissions from large enterprises has led to the oppression of coniferous forests, which are particularly sensitive to atmospheric pollutants that initiate oxidative stress in plants. A direct relationship between an increase in the content of pollutants in the needles and an increase the concentration of hydrogen peroxide – a "marker" of oxidative stress was noted (Fig. 1).

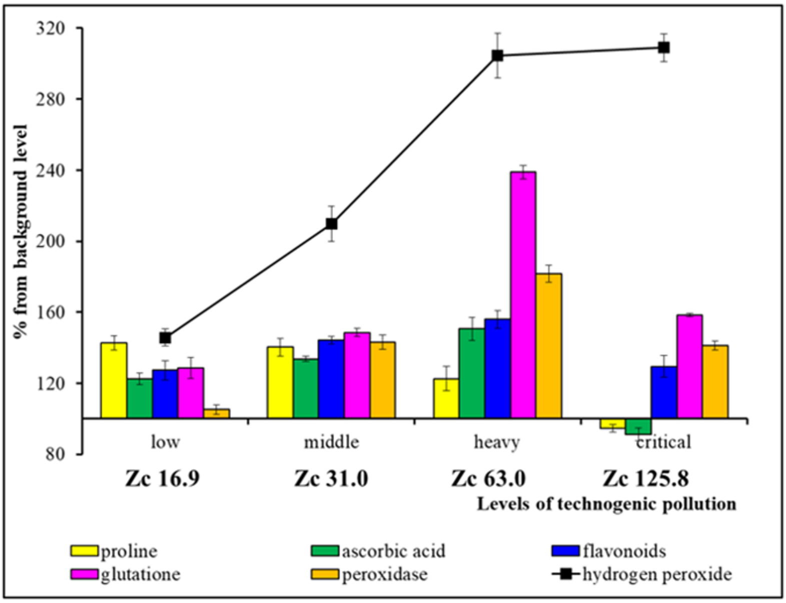

Fig. 1. Changes in the content of biochemical protection components in pine needles at different levels of technogenic pollution. Zc – total concentration coefficient of toxic elements.

At the same time, plants have a system of antioxidant protection, including low-molecular compounds and enzymes that preclude formation of reactive oxygen species. The effect of low-molecular-weight antioxidants, such as proline, glutathione, flavonoids, and ascorbic acid, was found to be activated under low level of technogenic pollution. Under a middle level of pollution, the content of these components increases and at the same time, the activity of enzymatic protection, primarily peroxidase, increases sharply (by 40%). With a heavy level of technogenic pollution, the concentration of both groups of antioxidants in conifers reaches its maximum. Therefore, depending on the level of technogenic pollution of needles, the degree of manifestation of the protective functions of enzymatic and non-enzymatic antioxidant components changes. A severe decrease in peroxidase activity and depletion of the pool of low-molecular-weight antioxidants occurs at a critical level of technogenic pollution (Fig. 1).

Study of the soil revealed an inverse relationship between the level of technogenic pollution and the soil resistance potential (Fig. 2). However, the peculiarities of the manifestation of the protective properties of the soil at different levels of its pollution were found. With a low level of pollution, the development of the turf process stabilized the humus and nitrogen content, as well as the C/N ratio. There is an increase in the proportion of stable humic acids that can retain nutrients in the soil solution and perform chemisorption (detoxification) in relation to the elements-pollutants. At a middle level of soil pollution, its protective function was largely due to an increase in cation exchange capacity. At the same time, there was an increase in the sorption activity of cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) of soil silty fraction in relation to the ions of the elements-pollutants. With a heavy level of pollution, the destruction of humus matter occurs, which causes a significant drop in the content of humic acids and an increase in the soil alkalinity. Alkalization results in enhancement of the adsorption capacity of SAC in relation to the elements-pollutants, that is, to their immobilization due to the formation of compounds with a low migration rate. At a critical level of soil pollution, a particularly high accumulation of toxic ions (Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, SO_4^{2-}) in the soil solution is registered, and their adsorption by the silty fraction of soils rises under condition the alkaline mode and the depletion of humus matter. At the same time, the decline in the soil resistance potential occurs gradually and takes a longer period in comparison with a faster development of tree-stand suppression. According to our observations, the soil, as a component of biogeocenosis, is more resistant to air pollutants than the phytocenosis.

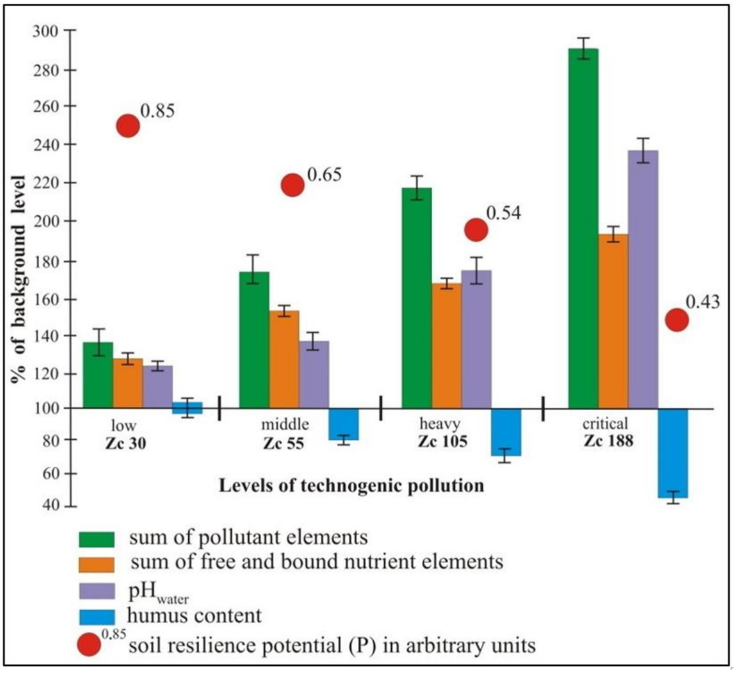

Fig. 2. Changes in pedochemical parameters and soil resistance potential at different levels of technogenic pollution. Zc – total concentration coefficient of toxic elements.

Forest ecosystems near urbanized areas are also affected by technogenic emissions, especially near highways. And the high recreational load, as one of the types of irrational forest management, in these forests is due to their use as recreation areas for citizens [5]. But still, the negative processes are less pronounced here than in the forests adjacent to industrial centers and tourist areas. Studies have shown that in the soil–plant system, the migration of biogene elements is disrupted due to the accumulation of pollutants in the horizons of the soil profile and binding of biogenes by them in SAC. The aerial accumulation of elements introduced with emissions by the assimilating phytomass of trees is also significant. In the course of biogenes binding in SAC, their migration to plant root systems is reduced, and when pollutants are absorbed in the process of gas exchange in plants, both mineral nutrition and photosynthesis are simultaneously disrupted. In the surveyed urban forests, these disturbances are combined. Accordingly, trees growth processes are suppressed, as evidenced by the decrease in morphostructural parameters and a fairly high level of crown defoliation (Tab. 1).

4 Conclusion

In the Baikal region, studies were conducted on forest ecosystems in the background (undisturbed) territories and in the territories exposed to anthropogenic factors – technogenic emissions, urbanization, irrational forest management (high recreational load caused by large tourist flows). The deterioration of the parameters of pine trees state and gray forest soil exposed to each of these factors was indicated. At the same time, the most pronounced disturbances of forest ecosystems were observed at middle and heavy levels of technogenic pollution and at high recreational load, which caused recreational digression of forests. The concentration of enzymatic and non-enzymatic antioxidant components in needles was found to reach its maximum at a heavy level of technogenic pollution. The study of soil protective properties indicated that the drop in the soil resistance potential under technogenic pollution occurs gradually and takes a longer period in comparison with the more rapid development of tree-stand decline.

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