Effect of Industrial Pollution on Sulphur Accumulation in the Needles of Scotch Pine (*Pinus sylvestris* L.) in the South-Western Transbaikalia

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Abstract

Effect of air industrial emissions of the main industrial hubs of Buryatia on the pine forests in water-collecting area of the Lake Baikal has been studied. Contamination of forest stands is estimated from accumulation of sulphur, a priority pollutant element, in needles of Scotch pine. Depending on the distance from sources of industrial emissions, zones of variable intensity of forest pollution are distinguished. The highest correlations between the sulphur content of needles and morphometry parameters of trees are revealed in the zone of severe pollution.

INTRODUCTION

During the last decades, atmospheric emissions of the industrial manufacturers are a powerful factor of negative environmental impact. This factor is responsible for the disturbance of stable functioning of ecosystems, including wood ecosystems, and causes their partial or full degradation. Negative effect of air industrial emissions on the major biological and ecological processes in wood ecosystems leads to a decreased biosynthesis of organic matter, to changed balance between CO_2 and O_2 in the biosphere, and with this to strengthening of «the greenhouse effect». Therefore, necessity in quantitative analysis and estimating the hazard of excessive ingress of pollutants into ecosystems with allowance for the response of various components of ecosystems to these actions becomes obvious.

Oxides of sulphur and nitrogen belong to the main contaminants of industrial origin. These compounds and acidic precipitation caused by them have both direct and indirect influence on the wood phytocenoses by changing soil characteristics that are important for plants. Accumulation of pollutants in vegetative tissues, primarily in assimilatory organs, is one of the most informative indicative factors of pollutant action upon the plants. Many explorers use sulphur content in the needles of trees as the main diagnostic attribute when estimating air industrial contamination of woods [1–3]. This is related to the fact that the level of sulphur in assimilatory organs, as a rule, reflects adequately a degree of emission load both on the plants and on the wood ecosystem as a whole.

The forests in the investigated Transbaikalia area experience the influence of industrial emissions, whose composition is dominated by oxides of sulphur and nitrogen, as well as by heavy metals. Sulphur dioxide emissions are of predominant abundance and they comprise more than 30 thousand ton per year [4]. However, no investigations were made previously into the action of air industrial emissions on the forests of the western Transbaikalia, which occupy over 80 % of the area of Buryatia and form a basis of steady functioning of its connatural complexes. The Basin of Selenga River that is the main tributary of the Baikal Lake and forms 50 % of aqueous runoff of the lake represents this area. The major industrial and agricultural potential of Buryatia is concentrated here.

The purpose of the present work is to study accumulation of sulphur in needles of pine trees that grow at different distance from industrial centres, to reveal spatial distribution of forest contamination in the south-western Transbaikalia, as well as to estimate a state of pine forest stands from variation in some morphometry parameters.

REGION, SUBJECT, AND METHODS OF RESEARCH

Inspections of pine forests in the south-western Transbaikalia were made in 2001–2004. The region is characterized by a low potential for self-cleaning of atmosphere from harmful impurities. This is caused by the mountain-kettle relief, inversion stratification of the atmosphere, and by a long-term period of low temperatures of air and soil. This promotes accumulation of pollutants in the ground layer of atmosphere and an increase of its contamination level.

The piny, larch, firry, cedar, birches, and mixed forests are distributed over the Transbaikalia territory. We have studied forest stands of one of the basic forest forming species, namely, Scotch pine that is distinguished in its high sensitivity to atmospheric toxicants. The total area of the investigated forests was of about 500 thousand hectares.

The research area is characterised by ripening and mature herb-cowberry, rhododendron, and steppificated pine forests of III–IV stand quality class, the reserves of which is estimated to be 150–250 m^3/ha. Soils are represented predominantly by the mountain soddy forest sandy ones, and pine-forest sands. Severe conditions of forest vegetation, specifically, the small (200–400 mm a year) precipitation quantity, dryness of air, the thin (10–20 cm) snow cover, and deep freezing of soil, determine here the low-productivity pine forests to form and, consequently, a weak stability against negative factors.

Inspection of the forest stands was conducted on the sampling areas (SA) that were defined according to procedures, which are adopted by the State forestry management [5, 6]. To reveal the features in spatial distribution of forest pollution by sulphur dioxide, transects from the large industrial centres in the direction of predominant atmospheric transport were defined. Sampling areas were located at the distance of 2, 10, 16, 40, 60, 100, and 180 km from emission sources.

The basic morphometry parameters that define the state of crown and outgrowths were determined in Scotch pine trees of the second age class on SA in the second half of vegetative period (early August). Needles of the second year of life were analysed for the sulphur content. Sulphur determination in needles and in the forest litter was performed in compliance with [7]; the mobile speciation of sulphur (KCl extract) in soil was determined by the procedure described in [8]. The background content of this element was determined on the SA that were located in pine forests, 50–200 km far from industrial centres. Sulphur concentration coefficient has been calculated following Sayet's procedure [9]. Statistical data processing was conducted by the procedure described in [10] with the use of Microsoft Excel 2000 package.

RESULTS AND DISCUSSION

Sulphur content under background conditions

Atmospheric pollution exerts both direct action upon the evolution of chemical composition of assimilatory organs (accumulation of pollutants, leaching of nutrition elements) and indirect action through modification of the nutrition conditions of soil.

However, to estimate an extent of this action, the knowledge of the initial (background) content of elements in the object under investigation is necessary. The background content of a chemical element represents an estimate of the average content and indexes of variation in the content of this element that were calculated for the sites located beyond the area of natural or technogenic concentration of the element [9].

The content of mobile sulphur in the background soils of the region in the upper (0–30 cm) layer varied from 0.16 to 0.63 mg/100 g. The average content of the element in the whole plurality of soils comprised (0.43±0.06) mg/100 g. In accordance with a scale of the soil sulphur supply [11], the soils in question should be assigned to the low-supplied series. Pine-forest sands contain the least quantity of sulphur (0.16 mg/100 g); sulphur content in a mountain soddy forest soil is almost 4 times higher.

The sulphur content of the forest litter on the same SA varied from 0.025 to 0.08 % from dry mass. The average quantity of sulphur in the litter was equal to (0.06±0.01) %. The close contingency in sulphur content between a soil and a forest litter has been revealed, as witnessed by high coefficient of linear correlation (0.89±0.17, $P = 0.99$, $t_{real} = 5.1$, $t_{theor} = 3.5$).

Analysis of literary data demonstrates that the background sulphur content in needles of a Scotch pine varies over a wide range (0.016–0.06 % from dry mass) and shows a peculiar variation range for each region [1, 12]. Average content of sulphur in the needles of a Scotch pine in the background forest stands of Transbaikalia was equal to (0.032±0.001) %; the variation limits were 0.026–0.036 % (the variation factor was equal to 11.6 %) (Table 1). According to the Verman's scale of nutrition element supply [cited from 13], this sulphur content of needles is assumed to be sufficient.

Correlation analysis revealed no significant dependence between sulphur content in needles and its content in soil ($r = 0.17$) or in forest litter ($r = -0.26$). This confirms the conclusions of some authors that chemical composition of needles of a Scotch pine under the background conditions has only a weak dependence on the content of elements in soil, conceivably, because of the capability of a tree's root system to capture the elements not only from soil, but also from rock [13]. In addition, the plants have the property of foliar absorption for such volatile elements as sulphur, fluorine, and iodine from the atmosphere.

Sulphur content under conditions of industrial pollution

We determined accumulation of sulphur in pine needles upon air technogenic pollution in the forest stands that were subject to an influence of three major and several minor industrial hubs. Ulan Ude industrial hub is characterized by the greatest quantity of emissions of polymetallic character due to the developed fuel and energy complex, machine-

TABLE 1

Sulphur content in needles of a Scotch pine in the background conditions

Place of sampling	Distance from source of emissions, km	Sulphur content, % from dry mass	Ratio to the average content*
Tayezhny settlement (Selenginskiy district)	60	0.032 ± 0.002	1.0
Oninoborsk village (Khorinskiy district)	160	0.026 ± 0.001	0.8
Udinsk settlement (Khorinskiy district)	100	0.034 ± 0.001	1.1
Ushkhayta village (Kizhinginskiy district)	120	0.034 ± 0.002	1.1
Okino Klyuchi settlement (Bichurskiy district)	80	0.034 ± 0.001	1.1
Small Kudara village (Kyakhtinskiy district)	100	0.026 ± 0.001	0.8
Ulyekchin settlement (Zakamenskiy district)	80	0.036 ± 0.001	1.1

*Average content comprises (0.032±0.001) % from dry mass.

engineering industry, and due to the existing building materials plants. The Gusinoozerskaya state district power station serves as the main source of air industrial emissions in the Gusinoozerskiy industrial hub. This power station works with the local brown coals of high sulphur content for the long time. (It should be noted that this industrial hub is presently at a stage of slump in production.) The main sources of air industrial pollution in Nizhneselenginskiy industrial hub are represented by Selenginskiy cellulose-cardboard integrated works (SCCIW), and the building materials plants, including cement and asbestos production.

One of the basic characteristics of geochemical or biogeochemical technogenic anomaly is its intensity, which is defined by a degree of accumulation of a pollutant element as compared to the natural background. An index of anomaly level for an element content is the concentration coefficient K_c , which can be calculated as a ratio between an element content C in the object under investigation with a technogenic load and its medium background content C_b: $K_c = C/C_b$ [9]. The elements, K_c of which is equal to or more than 1.5, are classed with elements of abnormal content.

Determination of sulphur content in soil in the vicinity of industrial centres has demonstrated that the level of this element exceeds the background value by a factor of 1.5–2. The largest content has been observed in the vicinity of SCCIW, that is 1.2 mg/100 g (K_c = 2), and Gusinoozyerskaya state district power station, 1.0 mg/100 g (K_c = 1.5). With increasing distance from the sources of emissions, the sulphur concentration in soil decreases and reaches the background values at the distance over 40 km.

Sulphur concentration in the forest litter in the vicinity of emission sources comprises 0.12 % (SCCIW), 0.1 % (State district power station), and 0.9 % (Ulan Ude), which is 2–1.5 times more than the medium background value (K_c = 2, 1.6, and 1.5, respectively). With the distance increased to more than 40 km, its concentration drops down to 0.05 %.

Under conditions of industrial pollution, the sulphur content of pine needles can exceed the background value by several times. Emergence of visible evidence of damaged needles, suppression of growth of vegetative organs, a decrease in length and weight of needles and outgrowths is observed with excess of background value by 40–60 %, according to one data [1, 14], and by 1.5–2 times according to alternative data [3, 15]. Given the strong suppression of coniferous trees, the sulphur content considerably increases and 3–5 times exceeds the background value [1, 2, 16].

Analysis of sulphur content in pine needles of industrial regions of Buryatia (Table 2) has demonstrated that pollution of forest vegetation with this element covers a significant territory and shows mosaic character. Its wide distribution in the region is aided by the existence of various sources of sulphur-containing emissions, namely, the fuel power plants, plants of pulp and paper industry, of the construction industry, and timber processing plants. In addition, significant amounts of sulphur are discharged into atmosphere during combustion of brown coals in urban thermal power stations. Concentration of sulphur in pine needles from industrial regions varies from 0.044 to 0.088 %.

Its highest content, which is 2–2.5 times more than the background level, is detected near the cities of Ulan Ude, Gusinoozersk, and Selenginsk settlement. Their emissions contribute to formation of the aureoles of medium or severe forest pollution. Accordingly, the sulphur content of the Ulan Ude neighbourhood exceeds the background by 2.3 times, whereas the position in a half-closed intermountain basin contributes to the accumulation of air industrial emissions on the adjoining ridges and to their distribution along the Uda River valley, one of the large tributaries of Selenga River. Meridian arrangement of Gusinoozersk intermountain basin, which is closed by ridges from the northwest and southeast, also promotes a precipitation of air industrial emissions within this basin and on the adjoining ridges where exactly the highest sulphur concentrations in pine needles are detected. Nizhneselenginskiy industrial hub belongs to one of the most sulphur-dioxide-polluted areas, especially in the vicinity of Selenginsk and Kamensk settlements. Sulphur content of pine needles exceeds here the medium background by 2.7 and 1.8 times

TABLE 2

Sulphur content and its concentration coefficient K_c in needles of Scotch pine under conditions of influence of atmospheric emissions from industrial hubs

Sampling place, distance from a source of pollution	Sulphur content, % from dry mass	K_c
Zones of severe pollution (50 thousand hectares)		
Gusinoozerskiy industrial hub:		
2 km from the state district power station	0.088 ± 0.001	2.8
8 km from the state district power station	0.064 ± 0.001	2.0
Nizhneselenginskiy industrial hub,		
Selenginsk settlement	0.086 ± 0.002	2.7
Ulan Ude industrial hub:		
Ulan Ude, 4 km from Thermal Power Station-1	0.075 ± 0.001	2.3
Thermal Power Station-2	0.064 ± 0.001	2.0
Zones of medium pollution (80 thousand hectares)		
Nizhneselenginskiy industrial hub:		
Kamensk settlement	0.057 ± 0.001	1.8
8 km far from the Selenginsk settlement	0.054 ± 0.001	1.7
Gusinoozerskiy industrial hub,		
16 km from the state district power station	0.055 ± 0.002	1.7
Ulan Ude industrial hub,		
15 km from Ulan Ude	0.048 ± 0.002	1.5
Kyakhtinskiy industrial hub,		
Kyakhta city	0.050 ± 0.002	1.6
Zakamyenskii industrial hub,		
Zakamyensk city	0.048 ± 0.002	1.5
Zones of mild pollution (250 thousand hectares)		
Gusinoozerskiy industrial hub,		
40 km from the state district power station	0.044 ± 0.002	1.4
Nizhneselenginskiy industrial hub,		
40 km from the settlement of Selenginsk	0.044 ± 0.001	1.4
Ulan Ude industrial hub,		
40 km from Ulan Ude	0.040 ± 0.001	1.3
Dzhidinskiy industrial hub		
Petropavlovka settlement	0.040 ± 0.001	1.3

respectively and the absence of terrain obstacles along the way of air industrial emissions facilitates their transport for significant distances. It should be noted that the use of sulphuric acid during decomposition of wood in SCCIW technology also could exert significant effect on sulphur pollution of not only vegetation, but soils as well.

Local sites of the investigated territory where the concentration of sulphur in needles exceeds the background concentration by a factor of 1.5–1.8 are located in the vicinity of less large cities and settlements, wherein the heating systems and some local manufactures (the cities of Kyakhta, Zakamensk, and Dzhida settlement) serve as sources of air industrial emissions. At larger distance from industrial centres, sulphur content of pine needles gradually decreases. Nevertheless, its level at the distance of 15–20 km exceeds the background values by an average of 1.6 times (K_c = 1.7–1.5), *i.e.* it is abnormal. Sulphur content in pine needles on SA, which are arranged at the distance of 40 km from emission sources, does not exceed 0.04 % (K_c = 1.2), with variation from 0.041 to 0.036 %. It is likely that this has only a slight effect upon metabolism of trees [3]. Concentrations of sulphur in pine

TABLE 3

Coefficients of correlation between sulphur content in needles and morphometry indexes of crowns of pine trees that grow at the different distance from a pollution source

Distance from a source of emissions, km	Degree of the crown defoliation, %	Coefficient of correlation					
		Life span of needles	Length of outgrowth	Mass of outgrowth	Number of needles	Length of one needle	Mass of 50 needles
2–8	0.71	–0.96	–0.98	–0.94	–0.83	–0.85	–0.32
20–40	0.47	–0.56	–0.59	–0.34*	–0.55	–0.22	–0.1*
Background (80–100)	0.17*	–0.26*	–0.37*	–0.35*	–0.24*	0.1*	0.12*

*Unreliable data.

needles, which were close to background values, have been revealed in the areas that are more than 60 km far from industrial centres.

Based on data about the changing index K_c for sulphur in pine needles under the influence of atmospheric emissions, four levels (zones) of Transbaikalia pine forest pollution with sulphur-containing emissions can be arbitrarily distinguished:

1) background level (K_c = 0.8–1.1), more than 60 km far from the sources of emissions, no pollution is observed;

2) mild level (K_c = 1.3–1.4), 40–60 km far;

3) medium level (K_c = 1.5–1.9), 10–20 km far;

4) severe level (K_c = 2.0–2.8), less than 10 km far from industrial hubs.

It was of interest to reveal interrelations between sulphur content in pine needles, in soil, and in the forest litter under conditions of industrial pollution. Correlation analysis has shown the existing direct dependence of sulphur content in soil on its content in the litter (r = 0.86, P = 0.95), weak positive dependence between a sulphur level in needles and in the forest litter (r = 0.47, P = 0.95), and no correlation between the concentration of sulphur in soil and needles (r = 14, P = 0.95). This enables making a conclusion that data about sulphur content of soil under conditions of technogenic pollution are of smaller indicative importance as compared to indexes of sulphur accumulation in needles, which is likely to be attributable to inhomogeneity in structure and buffer properties of soils.

Accumulation of pollutants in needles causes modification in its physiologo-biochemical indexes and in its functional state. This reflects on morphometry parameters and, as a consequence, causes the fall in stand productivity. Results of the performed correlation analysis have revealed dependence between sulphur content in needles and modification of some morphometry parameters of trees (Table 3). The highest correlation coefficients between the sulphur content in needles and the defoliation degree of crowns, life span of needles, length and weight of outgrowths, number of needles and their length are observed in the severe pollution zone (2–8 km far from emission sources). As the pollution level lowers, 20–40 km far from industrial centres, the reliability of correlations between the considered parameters decreases, whereas coefficients of correlation are unreliable under the background conditions. Hence, sulphur is among the significant factors, which have an influence on suppression of forest stands under conditions of severe pollution.

CONCLUSIONS

Based on the results of the performed research, it may be deduced that pollution of Transbaikalia forests by sulphur-containing pollutants covers significant territory and shows complex mosaic character. The highest concentrations of sulphur in pine needles have been revealed in the immediate proximity of large emission sources, less than 10 km far from them.

The tendency of the sulphur quantity in needles to increase is preserved in the territories adjacent to industrial zones, at the distance of 10–40 km. The sulphur content in pine needles that is close to or slightly over a background level can be found 80–100 km far from industrial hubs, as well as in downwind southern and western parts of Transbaikalia.

Dependence between the sulphur content in needles and modification of some morphometry parameters of trees has been revealed. In severe pollution zone, the highest coefficients of correlation between sulphur content in needles and a degree of defoliation of crowns, life span of needles, length and weight of outgrowths, the number of needles, and their length are detected. As the pollution level lowers, the reliability of correlations between the considered parameters decreases.

Negative effect of the elevated concentrations of sulphur dioxide of technogenic origin on the pine forests of the major water-collecting area for the Baikal Lake dictates the necessity of constant monitoring of sulphur content in the bioobject that is informative for this purpose, specifically, the needles of a Scotch pine. In addition, in the long term, when carrying out the nature protection projects it is necessary to reduce technogenic load on the environment of the Baikal region, which features the special conditions of wildlife management.

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