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MONITORING OF FOREST ECOSYSTEMS OF TAIMYR (Second communication. First communication in N. 3, 2017)

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In the study, based on the analysis of literary sources and the own research materials, the characteristic of the environmental situation in Taimyr is done, in connection with aerial technogenic impact of the Norilsk mining and smelting complex (NMSC). The dynamics of forest condition over the past decade in the area within 200 km or more from the complex is evaluated. The analysis was performed taking into account the landscape structure of the territory. The progressive drying of the large areas of the northern forests since the early 80's is registered. The dendroclimatic analysis of the increment of older larch trees in the zone of the NMSC impact, implemented by the method of revealing the main factors influencing the increment, showed that since the beginning of the 20th century, the instability of the increment of wood has increased due to the sensitivity of this tree species to changes in the temperature conditions of growth. To assess the extent of forest damage, an aerial survey was conducted in July, 2003, as a result of which zoning of the territory adjacent to the NMSC was carried out according to the degree of damage to the stands: dead stands, severely damaged stands and moderately damaged stands. An estimation of the productivity of stands and the degree of their damage by landscape locations was made. The negative role of sulfur compounds was assessed and contemporary measures for sulfur utilization were described.

Keywords: *Norilsk mining and smelting complex, industrial aerosols, northern forests, ecological catastrophe, Taimyr.*

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INTRODUCTION

Intensive development of Taimyr natural resources (as well as other northern territories of the USSR-Russia) has led to the formation of various branches of the national economy. They are nonferrous and coal metallurgies, diamond and gold mining industry, oil and gas industry, energetics and transport. In particular, since the end of the thirties of the 20th century, a powerful mining and metallurgical complex of the Norilsk mining and smelting complex (NMSC) has been developed, national economic significance of which cannot be overestimated. But with the increase in its capacity and the development of new deposits of copper and polymetals, the negative impact of the NMSC on the entire complex of Taimyr environmental conditions (air quality, forests, grazing lands, water and soil) has sharply increased in the last three decades. There is chemical, thermal, radioactive contamination and mechanical destruction of large areas, which were quite clean in the 30–50's of the 20th century. According to the data of V. M. Mel'nichenko (2012), and G. S. Varaksin and G. V. Kuznetsova (2016), zonal biocoenoses had already been on the verge of survival by 2012, many of them had already completely degraded and deserts of anthropogenic origin appeared. The concentration of toxic substances in the soil exceeded the natural background by 50–100 times, including dozens of times over the maximum permissible concentration of heavy metals: copper, nickel, cadmium, cobalt, lead, and zinc. The biological productivity of deer habitat and hunting and fishing grounds was sharply reduced. The dynamics of the rejection of the territories that became unusable for agriculture and industry is doubled within 12–15 years on an average and today more than a third of the entire territory of Taimyr lands has become useless. As a result, the traditional land use of the few indigenous peoples was significantly violated. Forests and forest ecosystems located south, southeast and east of the enterprises of the NMSC are exposed to a strong impact of toxic industrial aerosols and therefore, according to their present state, one can judge the existing ecological catastrophe on the large territory of Taimyr.

Aim of the study is to analyse and generalize data on current situation of negative impacts of Norilsk smelter to the environments, specifically to forest ecosystems of Taimyr.

MATERIALS AND METHODS

A considerable number of literature sources on the Norilsk issue was collected and analyzed by the authors of the publication. It can be partly viewed from the lists of references in Communications 1 and 2. In field expeditions, various research methods were used: establishing sample plots, aerial visual survey, routes with the selection of drill samples.

On the sample plots, full measurements of trees were carried out including diameters and heights of each tree, description of the tree stem, crown and top (morphometric data), with indication of the health condition of the trees and the degree of actual fruiting. The drill samples were taken from the sample trees for the radial increment analysis. The forest stands were divided into age classes, usually there were two or three of them, including the younger generation under the age of 100 years, and the older one at the age of over 200 years. The aerial visual survey was conducted in dry, sunny weather at minimum altitudes of 100–150 m above ground and at a reduced flight speed of 100–120 km per hour, which is quite achievable for the helicopter, in order to view the crowns of individual trees better. Here we were helped by the experience of aerial survey in the mountain forests of the Baikal region (Ziganshin, 1999).

During office analysis, a full forest inventory of the study plot data was carried out to obtain average forest inventory indices and tree distribution series by density and condition (by a particular density of trees, and not by diameter classes). The average health score of the forest state was assessed. Drill samples were processed according to standard methods (Shiyatov et al., 2000), and then subjected to statistical analysis.

Work on the collection of literary data and field expeditionary studies was carried out by the authors of the article in the period of 1980–2012.

RESULTS AND DISCUSSION

Spatial-temporal dynamics of technogenic weakening of forests in the zone of NMSC operation. Dendroclimatic analysis of the growth of high-aged larch-trees in the zone of the NMSC, carried out by the method of identifying the main factors affecting growth, showed that from the beginning of the 20th century, the instability of larch growth has increased due to the sensitivity of this species to changes in the temperature growth conditions (Simachev et al., 1992). Growth instability predetermined a strong larch reaction to the effect of technogenic emissions, which were an additional destabilizing factor causing the death of larch trees in large areas. Spruce relative stability confirms that the primary cause or background of the loss of larch forests in this zone is not only the emissions, but instability of growth, reducing the resistance of larch to severe climatic changes. This is also evidenced by the pattern structure of larch forests death.

Observations revealed that the unfavorable climatic conditions of the growing season of 1989 contributed to an increase in the stands' decline. After the cold summer of 1989, the maximum larch and spruce decay was recorded on 80 and 70 % of the study plots, correspondingly (Ivshin, 1993).

The radial growth of relatively young living and dead trees was studied in the Norilsk region. The average age of the trees of 50–60 years, and this created considerable difficulties in analyzing the features of the growth of individual trees (Schweingruber, Voronin, 1996). Specific polar conditions of growth multiplied by young age cause the appearance of various local variations in the dynamics of the width of annual rings, which are not always amenable to synchronization. A small annual increase in wood should also be noted here. Some years the width of the annual ring reaches only 0.1–0.2 mm. The advantages of this age group of forests can be attributed only to the fact that their decrease of annual rings is less frequent than in the mature trees and ripening stands (Fig. 1).

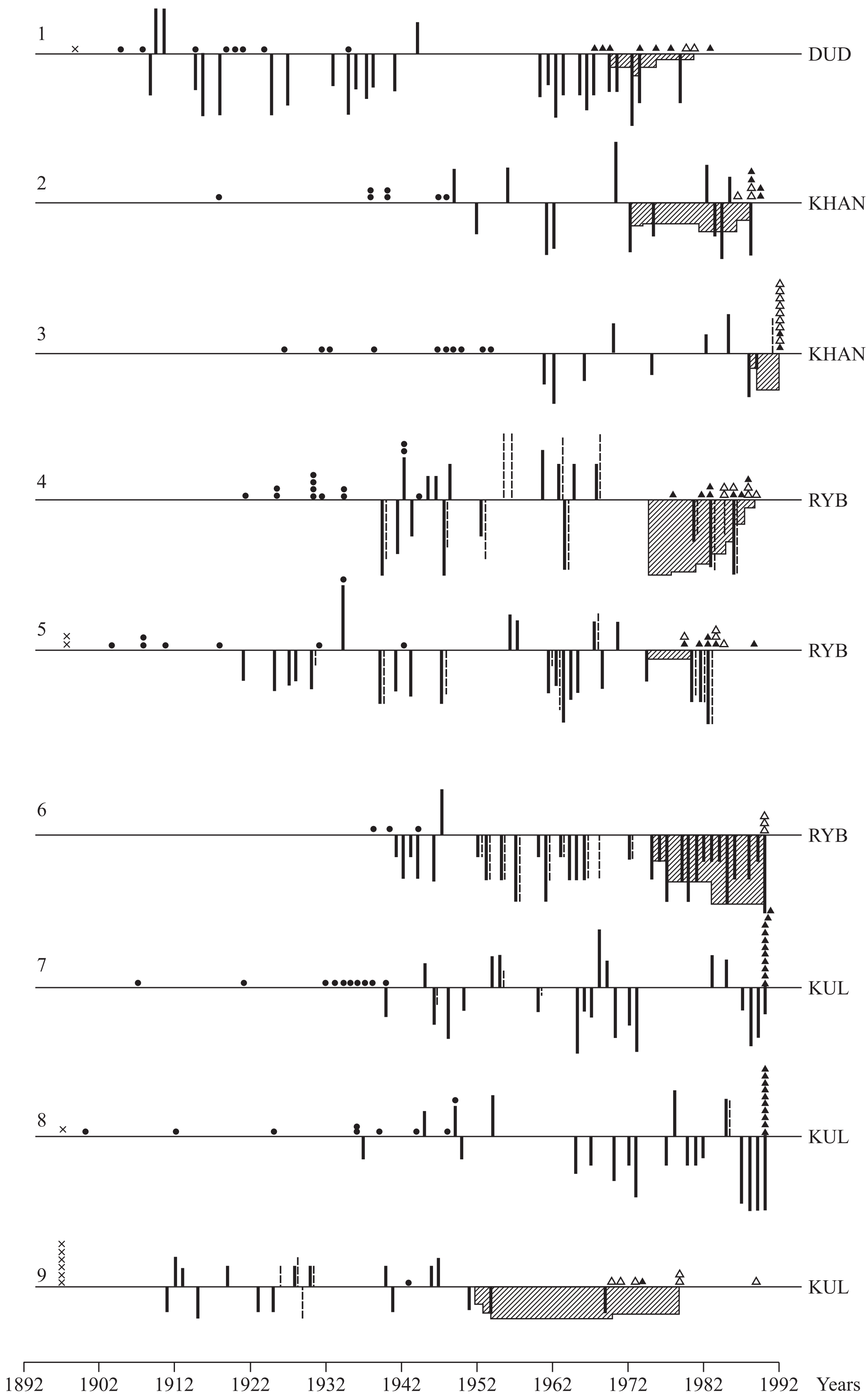

Fig. 1. Reduction of young larch growth weakened by the NMSC emissions in various habitats of the Norilsk valley: DUD – neighborhood of Dudinka town; RYB – Rybnaya river; KHAN – Khantaika river; KUL – Kulyumbe river (Schweingruber, Voronin, 1996). The rest of the notations are in the text.

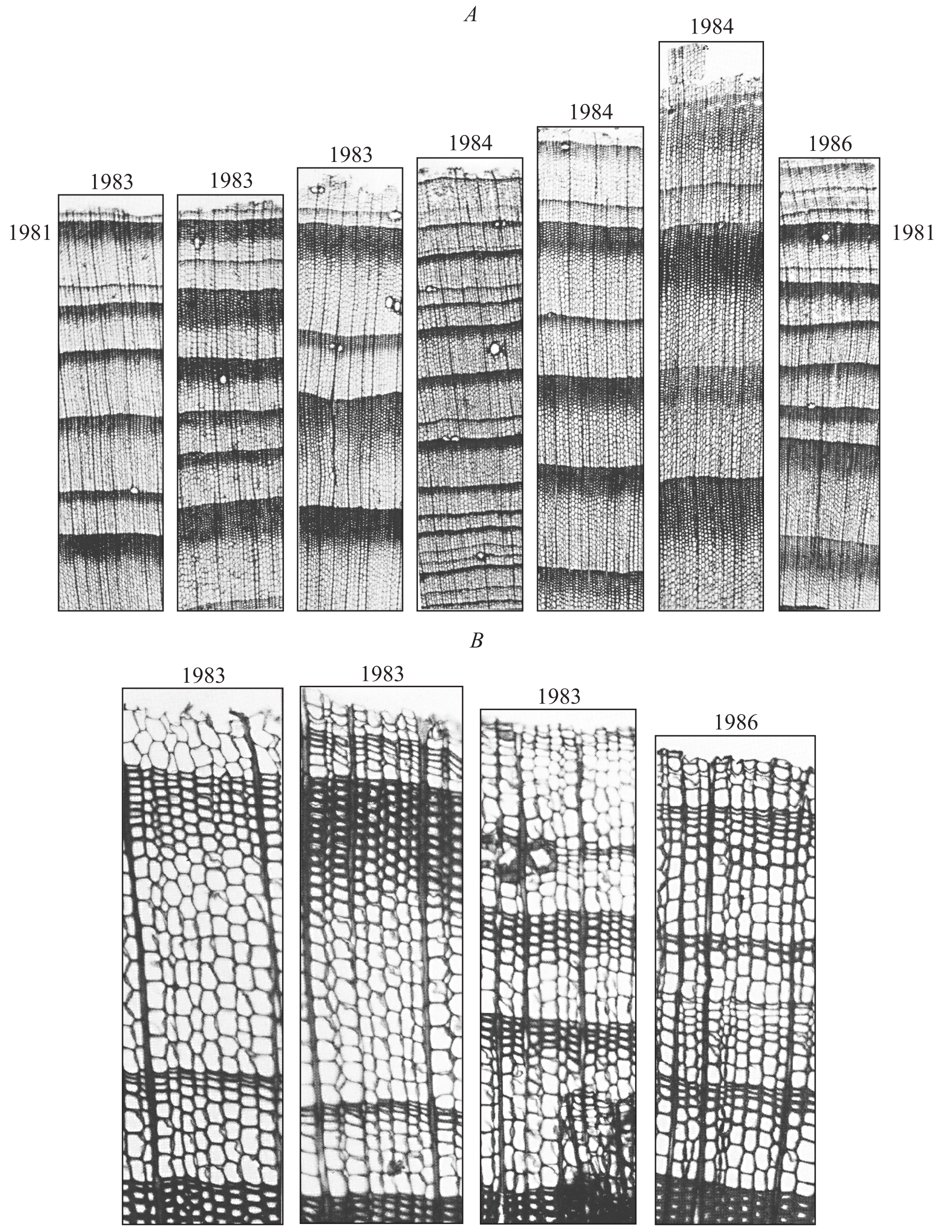

Fig. 2. Growth ring sequences from 7 dead larch trees from Rybnaya river, on a moraine site (*A* – overview 20 : 1). *B* – outer most growth rings, 100 : 1. Dating was primarily on the narrow rings of 1980 and 1982 and the broad ring with dense latewood of 1981. The trees died off between 1983 and 1986, most of them in 1983 and 1984. In most cases the moribund growth reductions lasted only 2 years (*A*). Death occurred either during the phase of early wood formation (*B*, 2 photos, left) or at the onset of latewood formation (*B*, 2 photos, right), but always before thickening of latewood cell walls began. Estimation of the moribund period as difficult because some surfaces considerably eroded (*A*) (Schweingruber, Voronin, 1996).

The precise dating of the death of individual trees acquires special importance while studying the effect of atmospheric pollutants on the forests of the Far North (Fig. 2).

The climatic conditions allow the dead tree stand to be preserved for a long time (more than 100 years) in the unchanged state. Often, one can draw the wrong conclusion about the recent death of the stand, while it occurred long before the time of the survey of the territory. It can be clearly seen in the example of dead trees in the KUL habitat (160 km south from the NMSC) (Fig. 1, line 9). In 1952–1955 summer temperatures increased in the study area (Vaganov et al., 1996) as was recorded by an increase in tree growth in this habitat. This warming contributed to an increase in the number of wildfires that are indicated by the presence of fire scars on tree stems. As a result of fire damage, the trees here sharply reduced their growth and went into a weakened state.

The first half of the 70's was noted for exclusively cold summer months (Vaganov et al., 1996) that led these trees to death. The surviving larch-trees at the time of our examination made two groups – healthy, having a green crown (Fig. 1, line 7) and weakened, with a large proportion of yellow needles in the crown (Fig. 1, line 8). The growth of both began to decrease significantly in recent years in proportion to their physiological state. The atmospheric pollution is the main reason for this decline. If the atmospheric pollution is just as intense, we should expect the further appearance of a deep reduction in the growth of these trees and their transition to a chronically weakened state.

The KUL habitat is a borderline for the impact zone of the NMSC airborne industrial emissions, being to the south from it at a distance of about 160 km. The depression of larch growth started here indicates that this zone continues to expand and this habitat will lose its borderline state and will soon be inside the damage zone. In due time a similar result was seen in the trees of the KAN habitat (120 km south from the NMSC). Samples of living and dead spruce were selected here. It was found that the effect of climatic factors causing the death of spruce was the opposite of that for larch. For a long time dying spruce experienced reduction in growth, caused by the negative impact of SO_2 emissions (Fig. 1, line 2). The summer of 1986 was unusually warm and arid for this region that was disastrous for weakened spruce (Vaganov et al., 1996). As a result, these trees dried. From the same period, there was a reduction in growth in trees that had previously maintained resistance. Thus, the synergism of negative climatic influences and the atmospheric pollution periodically leads to the death of the most weakened trees and causes the weakening of previously resistant trees.

In the RYB habitat (40 km south from the NMSC), larch died completely (Fig. 1, line 4, Fig. 2), spruce died for the most part (Fig. 1, line 5). Few spruce survivors experience very severe oppression (Fig. 1, line 6). The growth of these trees is greatly reduced and their death will occur in the coming years. The process of drying of the larch-trees, which had had a strong lethal growth reduction before death, was quite the same in this habitat (Fig. 1, line 4).

The lethal phase of growth reduction may differ in length and intensity due to various reasons (compare Fig. 1, line 2 and line 5). In the second case, the greater age of the trees was the reason for the decrease in their stability. These trees were older and died, having less intensive growth reduction. Younger trees continue to exist at a much greater growth depression.

In the DUD habitat (20–40 km north from the NMSC), the dying of larch-trees is primarily due to natural causes, although some additional effects of pollutants (Fig. 1, line 1) are also quite possible. The time-consuming process of drying of the studied group of trees points in favor of the first assumption, while in cases of toxic damage, the decay of trees occurs massively and in shorter periods (Fig. 1, lines 2, and 5).

The fact that the mass decline of trees weakened by gas-emissions occurs under the synergy of toxic load and negative influence of climatic factors is well illustrated by the dynamics of drying of stands, especially larch forests, established by A. P. Ivshin (1993). He noted the periods of the most intensive decline of trees in the early 70's, 1980 and 1988–1989. As it was shown earlier (Vaganov et al., 1996), these periods are characterized by very low air temperatures in June and July. Thus, the weakening and dying of forests in the Far North occurs against a background of changes in the temperature conditions of the growing season. Extremely cold winters play a very important role in this process.

Current state of stands in the research area. Comprehensive study of the state of natural ecosystems in the Norilsk industrial region, including forests affected by atmospheric pollution was started in 2001 by V. N. Sukachev Institute of Forest, Siberian Branch of the Russian Academy of Sciences.

A list of recent works of the Institute's staff on this topic is given in our First Communication (Ziganshin et al., 2017). Technogenic forest damage (increased percentage of dead-wood, crowns defoliation and tree leaf apparatus dechromation) along the direction of prevailing winds can be clearly traced at a distance of 200 km or more from Norilsk. We tried to assess the magnitude of the damage and the current state of the forests of the NID (Norilsk Industrial District) on the basis of aerial visual survey data during the flyovers of 2–7 July, 2003 with the purpose of selecting key areas for work on the ground[1] (Fig. 3).

[1] Ground-based study was carried out in key areas by the method of establishing permanent study area (PSA) with the collection of sample trees for studying forest inventory characteristics, their biological productivity and the monitoring system organization. To date, more than 40 PSAs have been laid and more than 120 samples of the main forest-forming tree species have been taken.

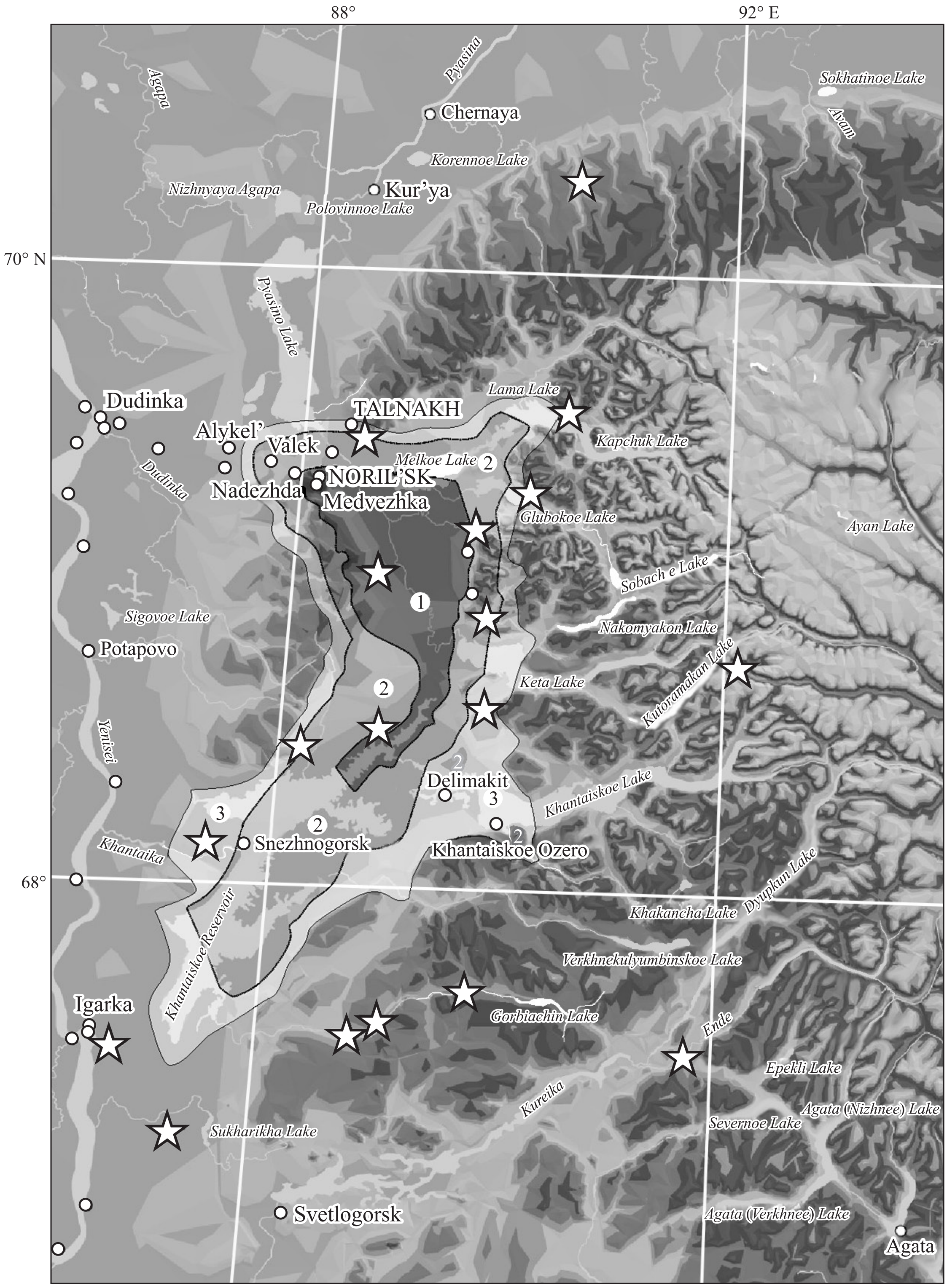

Fig. 3. Forests in the zone of industrial air pollution by enterprises of the NMSC. The marked territories correspond to the zones of: 1 – forest stands destruction, 2 – strong damage to forest stands, and 3 – moderate damage to forest stands. The key study areas are marked with asterisks.

The areas and boundaries of the dead (1), strongly (2) and moderately (3) damaged stands, that is, stands with well-marked signs of weakening caused by anthropogenic character, are plotted on the working map-scheme of damage to forests. The weak forest damage not marked on the map is observed to the east and south of the marked territories: on the slopes of the lake depressions (Lakes Khantaiskoe, Keta, Glubokoe, Lama), and also on the watershed divides of the Kulyumbe-Gorbiachin-Kureika rivers.

The territory with dead forest (1), including non-forest lands (screes, water, marshes), according to our estimates, occupies 345 thousand hectares, strongly damaged forests (2) – 800 thousand hectares and moderately damaged forests (3) – 675 thousand hectares, which is a cumulative total of: 345, 1145 and 1820 thousand hectares.

For all the territory of the study the shrub layer with a projective cover of 10–30 % and a height of 0.5–1.5 m is mainly composed of willows (*Salix lanata* L., *S. phylicifolia* L., *S. glauca* L., etc.). Along the channels of the watercourses and on the drained slopes of the southern exposition there are Dushekia (*Duschekia fruticosa* (Rupr.)), red currant (*Ribes rubrum* L.), honeysuckle (*Lonicera altaica* Pall.) and dog rose (*Rosa canina* L.). Widespread in the past, dwarf birch (*Betula nana* L.), juniper (*Juniperus communis* L.), green mosses and shrubs, with the exception of ledum (*Ledum palustre* L.) and crowberry (*Empetrum nigrum* L.), have now fallen out of the communities.

The area of dead forest stands was estimated in 2005 to approximately 345 thousand hectares. According to V. I. Kharuk et al. (1995), groups of living trees occurred in the depressions in the basin of the middle reaches of the Rybnaya river not so long ago (no more than 15–17 years ago). Now there are no living trees there. Even willow is oppressed. In August, by the end of the growing season, the occurrence of necrosis from the chemical burn of leaves on the willow bushes is approximately 60 %. Only in the line of contact between the zones (1) and (2) single specimens of living birch and spruce are preserved with growth suppressed to the extreme. On the elevated relief features, man-made wastelands without vegetation and soils are formed with access to the surface of underlying rocks.

In the zones of strong and moderate damage (~1475 thousand hectares), characteristic signs of man-made disturbance of forest cover are the increased occurrence of dead wood in the stands and the presence of chemical burns on leaf structure of woody and shrubby plants. It should also be noted that the disturbance of stands in the vicinity of the Khantaika water reservoir is due to two reasons; on the one hand it is the influence of pollution, and on the other – the effect of flooding.

Damage to larch – the main forest forming species – with pollutants, mainly with sulfur dioxide, is characterized by the following symptoms: the needle packing of branches and sprouting reduces, the size of growth decreases and the crown architectonics changes (the proportion of dry branches grows, and primary branches fall off). The reasons for the influence of pollutants are also the development of auxiblasts on the stem, accompanied by an increase in the length of the needles and a change in its morphology. There are also other morphological changes. Increases in needle size on the primary branches and germination of axial sprouts of strobiles have been noted (Fig. 4).

In acute injuries (burns), necrosis of needles is observed. After the burn, needle regeneration is possible, both from inactive buds and from damaged brachyblasts; that is why the category of the vital state of such trees did not decrease, but there was a burn mark.

According to the scale of the existing Sanitarnye pravila… (Sanitary Regulations…, 2006), there are six stand status categories: I – without signs of weakening; II – weakened; III – severely weakened; IV – drying; V – dead-wood of the current year; VI – dead wood of the past years. The stand status category on the study plot was established as a weighted average of the stems, including dead wood.

Forest inventory features of the forests of the Krasnoyarsk Krai were studied at different times by A. A. Dzedzyulya (1969), V. I. Pchelintsev (1984), A. I. Bondarev (1992), A. P. Abaimov et al. (1997) etc. As it was already noted above, tree vegetation here is mainly concentrated in the river valleys and on the slopes of the watersheds.

Mountainous and lowland forests are represented by clean and mixed larch forests. The average stand composition proportion is 70 % of larch, 20 % of spruce, and 10 % of birch (7L2S1B). The average productivity class (bonitet) of the main species is V (the lowest productivity), varied from Vb to III, medium relative basal area is 0.4, varied from 0.2 on placors (watershades) and terraces to 1.0 and higher in young floodplain forest stands. The stock of stem wood does not usually exceed 60–80 m^3/ha, but in the best, most favorable conditions – on the slope trails, in floodplains and on river fans-it reaches 150 and more, up to 260 m^3/ha, with an average height of larch 23–25 m and upper height – up to 30 m. Forest stands with an average age of 140–280 years predominate. The average age of the admixture of spruce is generally lower than the average age of larch, and its variability is higher than that of larch and birch. The birch age varies from 80 to 200 years. The larch forest stands are characterized by the highest values of taxonomic indices, while the birch forest stands – by the smallest ones (Table 1).

Low stacked-volume ratio of all tree species is also a distinctive feature of the subarctic forests.

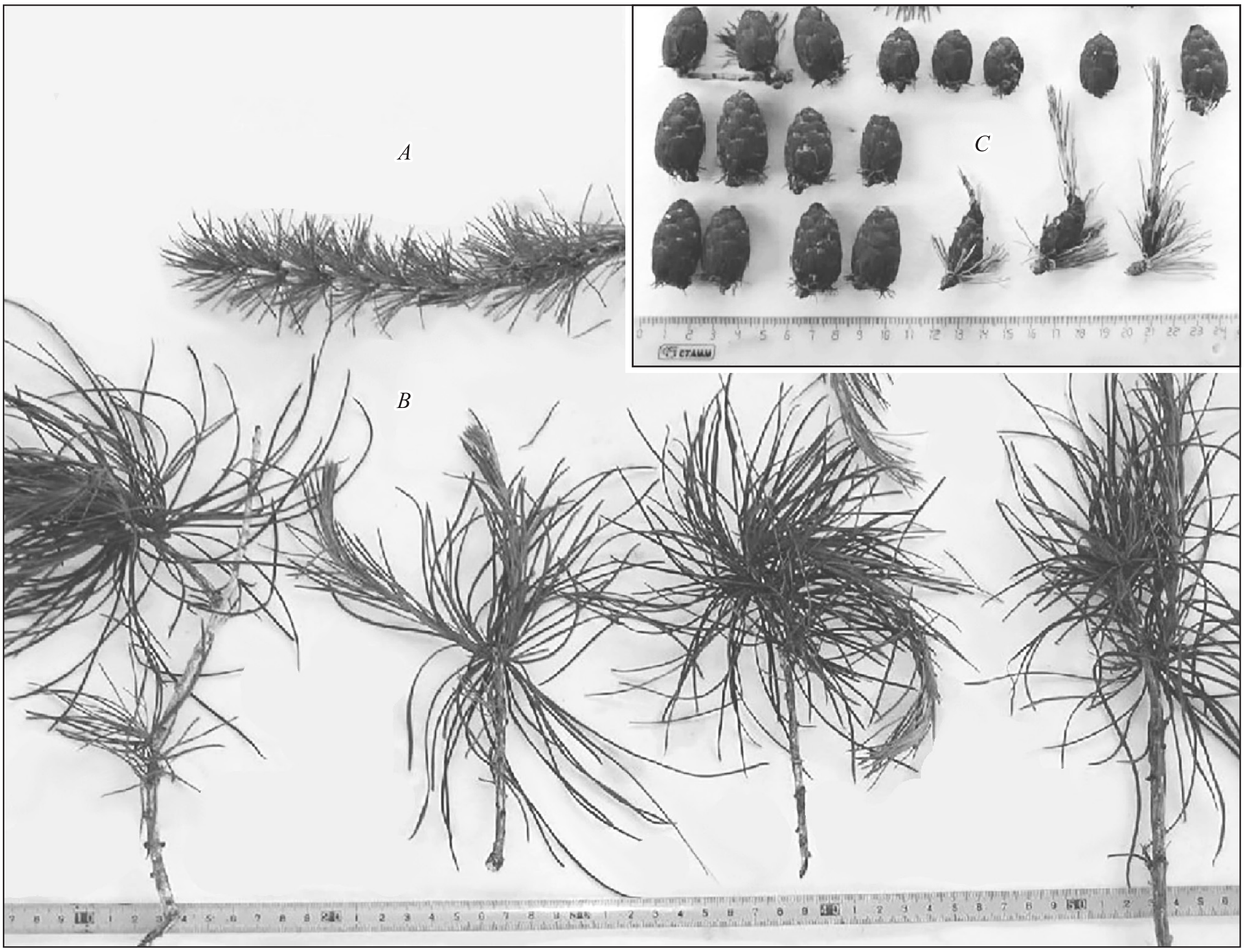

Fig. 4. Morphological transformation of larch under the influence of aerial and industrial pollution. *A* – a branch with needles of ordinary size; *B* – branches with needles enlarged to 14 cm in length (young larch on the bank of the Khantaika river in the zone of moderate damage to forests); *C* – mutations of strobiles (larch forest on the bank of the Tukulanda river in the zone of severe damage).

Table 1. Average forest inventory indices of forest stands of the main forest-forming tree species of the study area

Tree species	Age, years	Height, m	DBH, cm	Growing timber stock, m^3/ha
Larch	180	14.3	21.5	65
Spruce	170	11.9	16.6	19
Birch	90	10.0	10.4	10

Thus, the stacked-volume ratio of larch of the studied population is on the average 13 % lower than that of larch of other, more southern regions.

Differences in the productivity of forest stands allow us to single out (in the first approximation) the following natural territorial complexes (NTC):

Floodplain (valley) – the most generative and productive forest stands grow here. In mountainous conditions, these are narrow forest belts along the banks of rivers, or forests of the foot and lower parts of slopes bordering on the floodplain meadows (trails of the bedrock slopes, including the slopes of high terraces above the floodplain). Floodplains of the low lands consist of more extensive coastal forest strips (up to 200 m wide and more). In the floodplains and valleys, there are widespread closed mature and over mature conditionally uneven-aged forest stands with predominance of larch, there are also areas of young larch forests of post-fire origin, or formed on a stony river spit that had changed the river bed, or on the site of forest destroyed by ice drift.

Table 2. Examples of forest inventory characteristics of the stands within the framework of pointed NTCs

Damage degree of forest stands	Key area	NTC	Layer	Composition	Average				Timber stock, m^3/ha		
					category	age of basic tree species, years	height, m	relative basal area	growing forest	dead wood	part of dead wood, %
Background (conditionally)	Gorbiachin	Flood-point	I	10L*	1.2	147	13.8	0.7	147	1	1
		Terrace	I	10L	1.7	145	9.8	0.3	39	2	5
		Placor	I	10L	1.9	127	9.6	0.3	38	1	3
Weakly damaged	Lama	Flood-point	I	7L3S	2.8	270	18.3	0.5	136	19	12
			I	9S1L single B	2.2	296	18.8	0.5	160	21	12
		Placor	I	10L	2.1	129	10.0	0.2	22	3	12
Moderately damaged	Khantaika	Flood-point	I	10L + S	1.8	200	19.4	0.5	135	10	7
			II	8B1L1S	1.5	80	9.3	0.2	22	1	4
		Terrace	I	8L2S	2.9	220	15.7	0.3	65	22	25
			II	8B2S + L	1.8	90	9.0	0.2	23	1	4
Strongly damaged	Tukulanda	Flood-point	I	10L + S	2.4	289	23.4	0.4	148	16	10
			II	10B	3.0	80	11.1	0.2	24	9	27
		Terrace	I	9L1S	3.9	260	19.6	0.2	63	52	45
			II	10B + S	3.0	100	11.5	0.1	23	8	26
		Placor	I	10L	1.5	94	10.2	0.6	84	1	1
	Keto-Irbe	Flood-point	I	10L single B	2.2	116	15.6	0.5	111	18	14
		Slope	I	10L + S	3.1	253	19.3	0.2	70	17	20
			II	10B	3.0	137	11.1	0.2	39	10	20
		Terrace	I	10L single S	4.2	215	14.1	0.1	16	13	45
			II	10B	2.9	125	9.4	0.2	19	7	27

Note. * L – larch; S – spruce; B – birch.

Terrace is represented by relatively sparse conditionally uneven-aged forests of high terraces above the floodplain; they are more often dry and stony than marshy. Spruce and birch are usually predominant here, but pure larch forests are also common.

Slope is represented by closed mixed mature and over mature conditionally uneven aged forests of slopes of watershed ridges and knaps. There are basically larch-trees, spruce is less often met. The admixture of birch is found everywhere.

Plakor – sparse, more often uneven aged forests of flat or slightly convex tops of watersheds, forest stands at the upper forest boundary. Larch is prevalent.

The stands of the pointed NTC are well differentiated by gas resistance. The stands of the poorest habitats – stony river terraces and placors – are the most vulnerable to pollution. The stability of the stands increases with the improvement of the conditions of the site from the terraces and placors to the bedrock slopes, their trails, channels of temporary watercourses and floodplains of rivers. Thus, the vital state of the forest stands of floodplain complexes, even in the zone of severe damage, differs little from the state of the background (uncontaminated) forests, while the forest stands of high river terraces and placers of watersheds can in general be considered dead (Fig. 5, 6, Table 2).

Table 2 shows that the state of forest stands in the valley of Gorbiachin river indicates the absence of visible damages caused by the influence of air pollution. The productivity of forest stands is significantly reduced from floodplain locations to terrace and placor ones, and their condition deteriorates (the index of the category increases from I.2 to I.9).

In 2001, forest stands, confined to the upper parts of the slopes and the tops of flat watersheds, had obvious traces of technogenic damage (chemical burns of needles and leaves, dried shoots). In

Fig. 5. Forest stands in the zone of severe pollutants damage at Keto lake region. The floodplain and sloping stands are the most resistant to pollution (foreground). The stands of the above-floodplain terraces (central plan) and near the upper forest boundary can be considered dead (photo by A. P. Abaimov, 1997).

2003 there were no traces of the influence of pollutants. Here, on flat watersheds plantations are damaged occasionally, and affects appear after acid rain precipitation. These forests are attributed to conditionally background ones.

In the conditions of weak damage (the key area is Lama in 85 km east of Norilsk), the state of the forest stands corresponds to II.1–II.8 in the scale of Sanitarnye pravila… (Sanitary Regulations…, 2006).

These weighted mean values are determined through the values of the sums of the cross-sectional areas of trees of different categories of damage (Table 3).

The percentage of deadwood increases to 12 %. However, the damage here is still barely visible and appears only on the terraces, in the form of small parts of the affected forest with an increased occurrence of dead-wood and traces of chemical burn in the crowns of living trees (Table 3).

Fig. 6. Larch forests in the zone of moderate pollutants damage at the basin of the Kulyumbe river, western slope of the Putorana Plateau.

Table 3 shows the distribution of the sum of the cross-sectional areas of the forest stand (ΣG, m^2/ha) by species and status categories. Most of the larch stands (4.25 m^2/ha) are represented by trees of category V (new dead wood), i. e., that have died recently. The younger spruce is only weakened, and the birch stand is ½ thinned.

In the moderately damaged forests (Table 2, the area – Khantaika 8 km downstream from Snezhnogorsk and 150 km south of the pollution source), the affects become very noticeable. First of all, they include the presence of chemical burns of larch needles and an increased percentage of dead-wood (~ 25 %) in the forest stands of elevated relief features. Their condition worsens to category III.

Finally, in strongly damaged forests (key areas – Tukulanda (100 km to the south) and Keto-Irbe (85 km southeast of Norilsk), industrial damage to forest stands is more than obvious, especially on terraces. The quantity of dead wood here is about half of all trees, the state of the forest stands corresponds to category IV (drying out forest stands).

Thus, the forest stands of floodplain complexes in all cases, with the exception of the zone of forest destruction, are characterized by minimal damage, i. e. they have the greatest gas resistance. Young for-

Table 3. Characteristics of the area of the above-floodplain larch forest of shrubby-green moss composition 2L2S6B per area of 1 hectare

Species	Distribution of trees cross-sectional areas (*G*) by status category						ΣG, m^2/ha	Average for a tree stand			Timber stock, m^3/ha	
	I	II	III	IV	V	VI		Category of forest health status	DBH, cm	*H*, m	growing forest	dead wood
Larch	–	0.5	0.25	0.75	4.25	1.25	7.0	4.8	22	14	10	37
Spruce	0.5	1.0	–	0.25	–	–	1.75	2.0	12	9	9	0
Birch	–	1.0	2.25	1.75	0.75	3.75	9.5	4.4	9	7	25	23
Total:	0.5	2.5	2.50	2.75	5.00	5.00	18.3	4.4	–	9	44	60

est stands are more resistant than mature and especially over mature ones.

Various tree species react differently to air pollution. Larch is the first to be damaged and dry out. Spruce, as a species, is preserved longer than larch due to its uneven age. With the thinning of the upper canopy of forest stands, birch develops further, and is likely to be the last to die because of its ability to vegetatively reproduce

According to V. F. Tsvetkov and I. V. Tsvetkov (2003), stability of forest stands to industrial pollution is determined by the level of accumulated and current exposure. The degree of contamination of soil and living plant tissues is assessed as under the accumulated impact. The current impact is determined by the presence of pollutants in the air transit masses.

Technogenic pollution. Analysis of literature data showed that the background content of sulfur in spruce needles varies widely – from 0.04 to 0.17 % per gram of dry weight of needles. In more severe conditions, the sulfur content in the needles is much lower. For example, in the north of the Kola Peninsula, it varies between 0.04 and 0.08 % (Kryuchkov, 1991). According to 1989–1990 survey, needles of spruce, growing in Taimyr in the basins of the Tenegda river and the Ende river, contained 0.09–0.10 % of sulfur. Such an amount of sulfur in the spruce needles was assumed to be conditionally background (Zubareva, 1996). Information on the background sulfur content in the needles of Siberian larch is very limited. T. M. Vlasova and A. N. Filipchuk (1990) found that in the needles of larch growing in intact stands 320 km from Norilsk 0.22 % of sulfur is contained in dry mass. When conducting study in this area in 1989–1990, the sulfur content in the needles of larch growing in the basin of the Tenegda river, the Ende river, and the vicinity of the Khatanga settlement was assumed to be conditionally a background level. It was 0.20–0.25 % (Zubareva, 1996). The background content of sulfur in the leaves of various birch species also varies according to the literature data, depending on the conditions of growth. When carrying out study in the south of Taimyr in the zone of the NMSC emissions transfer in 1989–1990, the sulfur content in the birch leaves of 0.20–0.25 % to dry mass went for the conditional background level.

Thus, based on the analysis of literature data, the following levels of sulfur content in needles and leaves of the investigated tree plants can be considered as background: spruce – 0.09–0.15 %; larch – 0.18–0.25; birch – 0.16–0.25 %. The minimum level usually corresponds to unfavorable growth conditions (poor soils, severe climatic conditions), and maximum level is observed on rich soils. The stands, the needles and leaves of which contain sulfur at the background level, can be attributed to a group of conditionally pure.

Gaseous pollutants of the atmosphere (mainly sulfur dioxide) are considered as one of the main causes of weakening and destruction of forests in Western Europe. Areas with extensive large-scale forest degradation are well correlated with areas where the concentration of sulfur dioxide in the air is increased (Molski, Dmuchowski, 1998). The assessment of weakening of forest stands is based on the appearance of damage signs, changes in growth and productivity or changes in photosynthetic activity of trees. Other biotic and abiotic factors can cause the appearance of symptoms similar to damage by gaseous pollutants. Therefore, the identification of sulfur concentration in the leaf structure of trees is an integral part in determining the causes of stand weakening.

With a visual inspection of stands in the middle reaches of the Gorbiachin river (200 km from Norilsk), it was determined that a part of the trees has damage of the leaf structure in the form of the brown casse on the needles tips in coniferous shrubs and brown spots on the leaves of birch and deciduous shrubs. The revealed symptoms coincide with the visible signs of damage to woody plants with sulfur dioxide, pointed out in the literature. Trees with faded and yellowed foliage and needles are especially often found in the upper parts of the slopes and on the tops of flat and slightly convex watersheds.

Chemical analysis of birch leaves, spruce and larch needles showed that the average sulfur content in them is close to the background. However, sulfur concentration in samples of vegetation collected from different sites varies widely: spruce needles – 920 mg/kg; larch needles – 1775 mg/kg; birch leaves – 2140 mg/kg of dry mass. This amount of sulfur actually corresponds to the background level established earlier for this area (Vlasova, Filipchuk, 1990; Zubareva, 1996).

In the needles and leaves of trees growing in the vicinity of the Khantaika water reservoir (100 km south of Norilsk), an increased in 1.5–2.5 times amount of sulfur in comparison with the background level accumulates. Its concentration is 2570 mg/kg of dry mass in larch needles and 1520 mg/kg of dry mass in spruce needles, which is 1.5–1.7 times higher than the background. The most weakened stands are confined to excessively wet, locally waterlogged habitats, as a consequence of the flooding of the territory by the waters of the Khantaika water reservoir. A high level of sulfur accumulation in needles and tree leaves (1.8–2.0 times higher than background) is noted in the stands of Tukulanda river valley. In spruce needles, sulfur content is 2250 mg/kg of dry mass, which is 2.5 times higher than the background level. In larch needles, the sulfur content is 1.8–2.0 times higher than the background level. The maximum amount of sulfur in larch needles is found in stands growing at the upper boundary of the forest on a terraced ledge of a steep slope of 648 m above sea level.

According to A. V. Doncheva (1978), phytocenoses, occupying elevations, are primarily damaged. Vegetation of the upper parts of the slopes is more likely to experience contact with harmful impurities, an increased wind speed in these areas sharply reduces their gas resistance. In addition, high habitats are characterized by poverty of the ecotope and lack of soil moisture. It should be noted that over the past 10 years, the level of sulfur accumulation in the larch needles in the basin of the Tukulanda river has not changed significantly. According to the data of T. A. Vlasova and A. N. Filipchuk (1990) and O. N. Zubareva (1996), the sulfur concentration in the larch needles in this region varied within 2500–3900 mg/kg of dry mass, depending on the conditions of growth. According to these authors, stands in Tukulanda river valley belong to the category of strongly weakened.

Thus, based on the results of the chemical analysis of plant samples it has been found that, on average, an increased amount of sulfur accumulates in the forest stands in the vicinity of the Khantaika water reservoir: 2820 mg/kg of dry mass in the larch needles, which is 1.6 times higher than the background level; 1910 mg/kg of dry mass in spruce needles, which is 2.1 times higher than the background level; 2645 mg/kg of dry mass in the birch leaves, which is 1.2 times higher than the background. According to L. D. Rak (1985), such an increase in the amount of sulfur in the needles of Finnish spruce does not cause significant disturbances in the morphological characteristics of the tree. V. V. Kryuchkov (1991) believes that such sulfur content in spruce needles corresponds to the zone of the earliest stage of degradation of taiga ecosystems and can be traced at a distance of 80–90 km from the industrial site. During volley emissions of pollutants and in anticyclonic windless weather, air quality in this zone is worse than sanitary standards. The content of sulfur dioxide in the air of this zone is maximum one-time 0.07 mg/m^3, average annual – 0.05 mg/m^3. In the opinion of German scientists, sulfur can accumulate up to 1900–2300 mg/kg of dry mass with a weak effect of sulfur dioxide in the needles of European spruce. At this level of its content, the appearance of damage signs is already possible (Guderian, 1970; Stephan, 1982). In the needles and leaves of trees growing in the vicinity of the Khantaika water reservoir, the amounts of sulfur close to those specified in the literature accumulate. Consequently, they are constantly exposed to pollutants; this causes necrosis of needles and leaves, their premature fall, gradual weakening and death of trees and stands.

CONCLUSION

When moving to the north (from the Khantaika water reservoir to Norilsk), the weakened stands are replaced by dead wood. In the reception basin of the Rybnaya river, tree vegetation has now completely died. Since the late 60's of the last century, the area of the dried forest increased from 5 thousand hectares to 283 thousand hectares in 1989. In 2003 it amounted to 345 thousand hectares. The area of dead and damaged forests increased from 332 thousand hectares in 1976 to 550 thousand hectares in 1990, and in 2004–2005 it reached 1820 thousand hectares. The tendency is quite obvious. The rate of weakening and death of forest stands grew especially in the 1980s due to the launching of the Nadezhda plant and the increase in emissions of sulfur dioxide into the atmosphere. It is natural to assume that due to established attitude towards the nature of Taimyr in the near future, the damaged forests in the boundaries of the pointed zones will turn into dead ones, and the present dead woods, damaged in the past, will transform into other, less productive, grass communities through the stage of digression, so called «shrub tundra». These communities, in their turn, will transform into the final phase – a lifeless man-made desert.

In the most recent years, the optimization of sulfur recovery from waste gases at the copper plant of the Norilsk complex and the reconstruction of processing lines of flash smelting at the Nadezhda metallurgical plant, as well as the implementation of measures to increase the efficiency of the dust-purification, have led to a reduction in emissions of pollutants at the NMSC by more than 150 thousand tons. In 2010, the reduction of sulfur dioxide emissions, compared to 2009, amounted to 36.6 thousand tons (Perminov, 2011).

Heavy metals reduced nickel oxide, copper oxide and cobalt oxide emissions by 5.3, 12, 20.3 %, correspondingly. In 2010, machineries for collection of dust from gases (more than 300 units) were modernized. A plan for a phased reduction of emissions through the reconstruction of production and improvement of sulfur utilization was developed. General investments in environmental programs of «Norilsk Nickel» for the period of 2004–2010 reached 75 billion Russian rubles (Perminov, 2011).

There is a return to the practice of the Soviet time to protect the environment. This is good news. At the same time, it should be noted today that the technologies of the last thirty years have led to a genuine ecological catastrophe in the Taimyr Peninsula. The forests have been brought to ruins, pastures, soils, rivers and lakes have been polluted.

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МОНИТОРИНГ ЛЕСНЫХ ЭКОСИСТЕМ ТАЙМЫРА
Сообщение 2 (Сообщение 1 в № 3, 2017 г.)

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В работе на основании анализа литературных источников и материалов собственных исследований дается анализ экологической обстановки на Таймыре в связи с аэротехногенным воздействием Норильского горно-металлургического комбината (НГМК). Оценивается динамика состояния лесов за последние десятилетия в полосе как в непосредственной близости, так и на расстоянии до 200 км и более от комбината. Анализ проведен с учетом ландшафтной структуры территории. Отмечено прогрессирующее с начала 80-х гг. усыхание больших массивов северных лесов. Дендроклиматический анализ прироста высоковозрастных деревьев лиственницы в зоне влияния НГМК, произведенный методом выявления основных факторов, влияющих на прирост, показал, что с начала XX в. у лиственницы увеличилась нестабильность прироста древесины, обусловленная чувствительностью этой древесной породы к изменениям температурных условий роста. Для оценки масштабов повреждений лесов проводилось аэровизуальное обследование в июле 2003 г., в результате которого выполнено зонирование прилегающей к НГМК территории по степени повреждения древостоев: погибшие древостои, сильно и умеренно поврежденные. Произведена оценка продуктивности древостоев и степени их поврежденности по ландшафтным местоположениям. Дана оценка отрицательной роли серных соединений и названы современные мероприятия по утилизации серы.

Ключевые слова: *Норильский горно-металлургический комбинат, промышленные аэрозоли, северные леса, экологическая катастрофа, Таймыр.*

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