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THE ASSESSMENT OF SUBTUNDRA FORESTS DEGRADATION BY DENDROCHRONOLOGICAL METHODS IN THE NORILSK INDUSTRIAL AREA

Key-Words: subtundra forests, tree-ring analysis, pollutants, forest degradation, Putorana Plateau.
Parole chiave: foreste di subtundra, analisi dendrocronologica, sostanze inquinanti, degrado forestale, pianura Putorana.

Abstract

Conifer forests at the northern timberline south of Norilsk in Central Sibirea die dramatically since the establishment of powerfull smelters in the seventies. Dendrochronological growth and mortality determinations clearly show that radial growth decreased and the mortality increased under the influence of Sulphurdioxide.

Introduction

Subtundra forests of the Norilsk industrial area (the western part of the Putorana Plateau) have been degraded intensively during the last 30 years over a large territory under the influence of phytotoxic air pollutants emitted from the Norilsk mining and metallurgical group of enterprises (NMMG). This represents one of the largest source of industrial contamination not only in Russia but in the world. During the last decade many investigations have been carried out in this area devoted to evaluating the quantity of emitted air pollutants, their transportation from their source of emission (VLASOVA, PHILIPCHUK 1990; MENTSHIKOV 1991), the accumulation and migration of phytotoxic pollutants in plants, soils and water (VLASOVA, PHILIPCHUK 1990; MENTSHIKOV, VASILJUK 1991; MENTSHIKOV1991; VLASENKO, VASILJUK 1992), the evaluation of scale and intensity of natural ecosystem degradation, especially forests (VLASOVA, PHILIPCHUK 1990; PHILIPCHUK, KOVALEV 1990; MENTSHIKOV 1991, 1992), and the organization of ecological monitoring systems (VLASOVA, PHILIPCHUK 1990; IVSHIN 1991, 1992; SIMACHEV ET ALII 1992; KHARUK 1993).

The aim of this study, conducted during 1986-1990, is to reconstruct the mortality and growth of the spruce-larch stands and to reveal the main natural and anthropogenic factors which determine the forest state in the zone of impact of NMMG emissions. Some results of this investigation have been published in IVSHIN (1991, 1992).

Natural conditions and forest disturbance characteristics

The study area is situated in the western and south-western parts of the Putorana Plateau. The Putorana Plateau, with maximum altitudes up to 1700 m a.s.l., is heavily eroded and contains deep hollows with large lakes (Fig. 1).

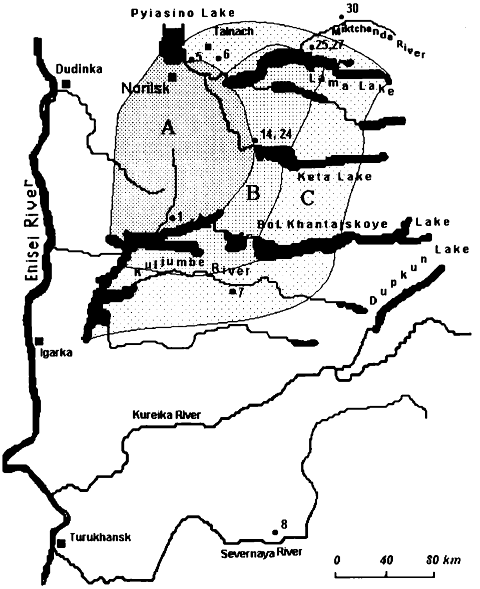

Figure 1 - Location ot the permanent observation plots and the zonality with various degree of forest degradation (A - dead and daying-off stand, B - heavily damaged stands, C - weakly damaged stands).

The climate of the area is very continental, continentality increases from the north-west to the south-east. The amplitude of the mean monthly air temperature is 42 to 48°C. The mean annual temperatures range from -10°C in the north to -8°C in the south. The coldest month is January (-27 to 32°C), while the warmest is July (+12 to 14°C). The absolute minimum air temperature reaches -60-64°C, the absolute maximum is +31° to 32°C. The number of days with mean daily temperatures above 5°C are 70 to 85 (from the beginning of the second week of June to the middle of the first week of September), above 10°C are 40 to 45 (from the end of June until the end of the second week of August). The average annual precipitation in the Norilsk valley is 400-500 mm, in the mountain areas it is 600-1000 mm. During the warm period of the year (June-September) about 50% of precipitation is dropped, mainly during the second half of this period. The formation of the stable snow cover takes place at the end of September, with the snow melt beginning during the first week of June. The depth of the snow cover at the end of winter is 70 to 80 cm. The south-eastern and southern winds prevail from October until March. In May-September the northern and north-western winds becoming prevailing (Atlas of the Arctic, 1985; Climatic atlas of the USSR, 1960, 1962).

The northern part of the Putorana Plateau is situated within the forest-tundra zone, while the southern part lies within the northern taiga subzone. Larch open forests prevail. The eastern border of Siberian larch (*Larix sibirica Ldb.*) distribution and the western border of Gmelini larch (*Larix gmelinii (Rupr.) Rupr.*) distribution are in this area. There are hybrids in the belt of contact of these larch species which are named Chekanovsky larch (*Larix X czekanowskii Sz.*). Siberian spruce (*Picea obovata Ldb.*) and mountain birch (*Betula pubescens Enrh.*) are admixed tree species.

Industrial development of this region began at the end of the 1930's in connection with the discovery of deposits of polymetallic ores (copper, nickel, cobalt and others). NMMG, before the end of the 1960's, had used low sulfuric raw material and its emissions had little impact on the state of the forests. At the end of the 1970's and at the beginning of the 1980's, raw materials with high contents of sulphur began being used and the large Nadezdinsk smelting plant started operation. As a result, the emission of phytotoxic pollutants into the atmosphere has increased considerably. According to data published by VLASOVA, PHILIPCHUK (1990) the total quantity of dust and gaseous substances emitted from all sources was 2349 thousand tons in 1980. The volume of emissions has increased until 1985 when the maximum amount of pollutants (4845 thousand tons) was emitted. In the middle of the 1980's, the decontamination facilities and the sulphur utilization department were put into operation. The volume of pollutants has decreased slightly but continues to be very high (4200-4400 thousand tons per year). The main part of phytotoxic pollutants is gaseous, from 50 to 77% of their total quantity in separate years. The main gaseous pollutant is sulphur dioxide (93-98%). From 1980 to 1989 the tendency of increasing dust emissions and decreasing gaseous emissions is observed (VLASOVA, PHILIPCHUK 1990). The maximum concentration of sulphur dioxide is located within 3 km of the source of emissions (5 mg/ cubic meter). High concentrations of sulphur dioxide are observed at distances of 20 and 26 km. (2.25 and 0.46 mg/cubic meter correspondingly) (MENTSHIKOV 1991). As pollutants are emitted from the tall smoke stacks (up to 200 m), they are transported great distances from their source.

The first visual signs of mass disturbance and the dying-off of forests in the vicinity of Norilsk city were noted in 1968. Later, in connection with the increase of phytotoxic pollutant emissions, the intensive forest degradation continued. Systematic investigations of the forest state from 1976 have been carried out by the Brjansk inventory expedition (PHILIPCHUK, KOVALEV 1990). In 1976 the area of damaged and dead stands was 322.5 thousand hectares. Of those, the main portion was the damaged stands (42%). The area of dead stands, those which possess more than 81% of dead and dying-off trees, has been increasing continuously, and reached 283,2 thousand hectares in 1989. At present, the total area of the damaged and dead stands is about 550 thousand hectares. The largest areas of such stands are placed to the south and southeast from Norilsk city (Fig. 1). In 1976 the border of the weakened forests in these directions was at a distance of 90 km from the source of emissions and at present it is at a distance of 170 km. The dead forest border during 1976-1989 has moved in these directions from 20 to 120 km (PHILIPCHUK, KOVALEV 1990). In recent years an intensive forest degradation has taken place in other directions, in particular to the east and north-east of Norilsk city. In these directions the border of the dead forests is now at a distance of 35 km and the damaged forests are at a distance of 90-100 km.

Objectives and methods

Tree-ring data in combination with annual visual observations on the permanent plots during 1986-1990 were used to reconstruct the forest state and to reveal the main limiting factors which influence the growth and state of stands. These techniques focused on the comparison of state and growth of stands growing in the polluted and unpolluted sites, and on the comparison of tree growth before and after the beginning of the pollutants influence in the contaminated sites.

Typical of this area, larch forests prevail and the forest degradation under the influence of the pollutants is associated with the dying-off of larch. The main objects of the study were larch species. Siberian spruce and mountain birch were the secondary study objects.

The state and growth of forest stands were studied in plots which were chosen at distances of 15-320 km from the emissions source along the next two transects: the south-east one (prevailing direction of winds in summer) and the north-east one (rare recurrence of winds in summer) (Fig. 1). Each transect has 5 plots which characterize the stands various degrees of the damage, from the conditionally healthy ones to those almost dying-off. All trees on the permanent plots were numbered and measured. Annually from 1986 to 1990 every tree was visually examined for such morphological indices as crown defoliation and leaf dechromation. To reconstruct the stand mortality dynamics, determinations of the time of death of the trees were made. The estimation of the calendar date of the last wood layer in tree was made by the cross-dating technique (DOUGLASS 1919). The cuts were taken at 20-100 cm and 2/3 of trunk height from 101 dead standing larch trees, including plot 1 (34 trees), plot 14 (26 trees), plot 24 (24 trees) and plot 27 (17 trees). Cores were taken from living trees at a height of 30-100 cm. The width of tree rings was measured with an accuracy of 0,01 mm. Absolute dating of annual rings was made by crossdating the ring-width curves. The calculation of ring-width indices was carried out by means of the corridor method (SHTYATO 1986). The biggest difficulty was to draw the maximum curve during the period of a possible influence of pollutants (after 1960). To draw this part of the curve the following rule was used: the inclination of the curve must be the same as during the previous 20-30 years. Ten tree-ring chronologies for each plot were developed. Brief characteristics of these chronologies are shown in Table 1.

All of the mean chronologies were tested

Number of plot	Location	Distance from Norilsk city	Altitude m a.s.l.	Horizontal canopy, %	Mean age, years	Average height, m	Average DBH, cm.	Species	Number of trees	Time interval	Mean sensitivity
					North-eastern transect						
5	Slope	15	70	80	170	13.0	18.0	L.s.	21	1683-1988	0.51
6	Slope	30	70	40	160	12.0	17.5	L.s.	21	1722-1988	0.43
25	Slope	80	90	60	160	13.5	22.0	P.o.	20	1698-1988	0.34
27	Slope	80	75	30	170	13.0	21.0	L.c.	11	1631-1986	0.49
30	Valley	100	175	80	190	14.5	24.0	L.c.	18	1670-1987	0.49
					South-eastern transect						
14	Slope	80	110	50	200	11.5	15.0	L.c.	12	1674-1986	0.50
24	Slope	80	100	70	115	16.0	16.0	L.c.	21	1857-1987	0.47
1	Valley	100	90	60	250	21.0	33.0	L.s.	10	1625-1986	0.48
7	Valley	170	120	60	160	19.0	26.0	L.c.	17	1728-1988	0.44
8	Valley	320	150	10	110	8.0	16.0	L.c.	20	1850-1988	0.34

Table 1 - Brief characteristics of the permanent observation plots and the mean tree-ring chronologies (L.s.-*Larix sibirica*, L.c.-*Larix chekanowskii*, P.o.-*Picea obovata*).

using the AR, MA and ARMA models (Box, Jenkins 1970). To reveal climatic factors which limit tree growth in-this area, regression analysis on principal components analysis was used (Cook 1987). For estimation of response functions the next climatic data were used: monthly temperatures for 1900-1990 from Dudinka station which is placed 80 km to the west from the city of Norilsk and monthly precipitations for 1900-1990 from Turukhansk station which is placed 400 km to the south from the city of Norilsk. The response functions were calibrated and verified using data of 1901-1930 and 1931-1960 time intervals. Also the calibration equations based on climatic variables from 1901 to 1960 were used to develop the predicted growth indices during the period of contamination (1961-1989).

Results

Reconstruction of tree mortality

On the basis of visual observations in 1986-1989 in plots 1, 14, 24 and 27, the exact year of death of 15 larch trees was exactly fixed. One tree died in 1987, seven trees in 1988, and seven trees in 1989. From these trees, cuts were taken to determine the accuracy of the determination trees death by dendrochronological methods. Analysis of the annual ring-width variability has shown that these trees had very narrow rings during the last 8-10 years of their life. For this period of their life, partly and completely missing rings are typical. At 2/3 height of the trunk, there are 1-4 rings more than at the base of the trunk. When rings are narrow and their annual variability is weak, it is difficult to determine the exact location of missing rings. Only one tree out of the fifteen did not have missing rings. The time of death for this tree was determined with an accuracy of one year. The remaining trees had from 1 to 5 missing rings, with an average of 2-3 missing rings. Such accuracy of ring dating is quite enough to reconstruct the trees mortality dynamics in larch stands. In this area the sapwood covered with bark preserves an annual structure during about 30 years after a tree's death. If a tree, or part of tree, is not covered by bark, the annual structure of sapwood is preserved much longer. This means that the dating of a tree's death with an accuracy of 5 years can be done in 30-50 years after their death.

The trees mortality data before the beginning of a pollutants influence in this plot were used as the standard which characterizes the mortality in the natural larch stands.

In plot 1 from 1925 to 1970 the average intensity of tree mortality in relation to the number of living trees during this period was 0.11% per year. Taking into account that some dead trees had fallen by this time and they have not been dated, the natural intensity of tree mortality can be increased 2-3 times. In such a case one can be sure that in plot 1, during 1925-1970, the tree mortality was no more than 0.2-0.3% per year. Tree mortality has increased sharply since 1970 and the maximum value has been reached during 1985-1989. During this time the intensity of mortality was 5.08% per year. In other words, the mortality has increased more than 20 times in comparison with the period before pollution began. A similar intensity of mortality was also found in the other plots. In plots 24 and 27 the abrupt increase in mortality began in 1975-1979, that is 5 years later than in plots

1 and 14. The portion of dead standing trees in relation to their total quantity before 1970 was from 9 to 20%. During the last 20 years this portion has increased significantly, and in plots 1, 14 and 27 it has reached 49-64%. In the plot 24, where a much younger stand grows, the portion of the dead standing trees was 28%.

Reconstruction of tree-growth

The tree-ring chronologies developed in this study (Table 1) have a very high sensitivity (sensitivity coefficient varies from 0.34 to 0.51). The larch chronologies from plots 5, 14 and 27 have the highest sensitivity. This is evidenced by the high annual variability of growth indices which can be interpreted as a strong climatic signal. In the study area, the chronologies are very similar. The synchronization coefficient among the larch chronologies varies from 75 to 91%. The correlation coefficient varies from 0.55 to 0.92. The highest similarity is observed among the larch chronologies obtained for the slope sites, the lowest similarity among the larch chronologies obtained for the valley sites and among the larch and spruce chronologies.

There is a relationship between the current year and the previous year's growth. The growth of the previous year is more highly correlated (correlation coefficient is 0.3-0.4). For seven out of the ten chronologies an AR(3) model was selected, for two chronologies an AR(1) model and for one chronology an AR(5) model. It was discovered that during the periods with high June temperatures, the autocorrelation was increased significantly and the obtained chronologies are not fully stationary. This is why the mean chronologies, without removing the autocorrelation, were used later on.

The analysis of correlation (r), determination (r^2) and regression (b) coefficients obtained between growth indices and various climatic characteristics has shown that the air temperatures of the summer months, particularly June and July, make the largest contribution to larch growth variability. Between the mean tree-ring chronologies obtained and June temperatures for 1901-1960, the mean value of "r" is 0.45 (from 0.33 to 0.57 in separate chronologies), of "b" is 0.22 (from 0.10 to 0.30). With July temperatures, "r" is 0.49 (from 0.32 to 0.63) and "b" is 0.37 (from 0.23 to 0.47), with August temperatures, "r" is 0.12 (from 0.06 to 0.27) and "b" is 0.22 (from 0.16 to 0.27). The mean dispersion percent explained by June and July temperatures is 36.5% (from 13 to 46%). The spruce indices (chronology 25) are most highly correlated with July (r=0.51, b=0.37) and June temperatures (r=0.38, b=0.15). August temperatures do not correlate well with spruce indices (r=0.04, b=0.03). The mean dispersion percent explained by June and July temperatures in the spruce chronology is 30%.

There are differences in the relationships between larch indices and summer temperatures during various time intervals (Fig. 2). During the period 1901-1930, June temperatures had less effect on larch growth (r=0.30, b=0.08) in comparison with the period of 1931-1960 (r=0.55, b-0.26). On the contrary, August temperatures were more influential from 1901-1930 than from 1931-1960 (r=0.21, b=0.26 and r=O.10, b=O.11, respectively). The role of July temperatures was approximately the same in

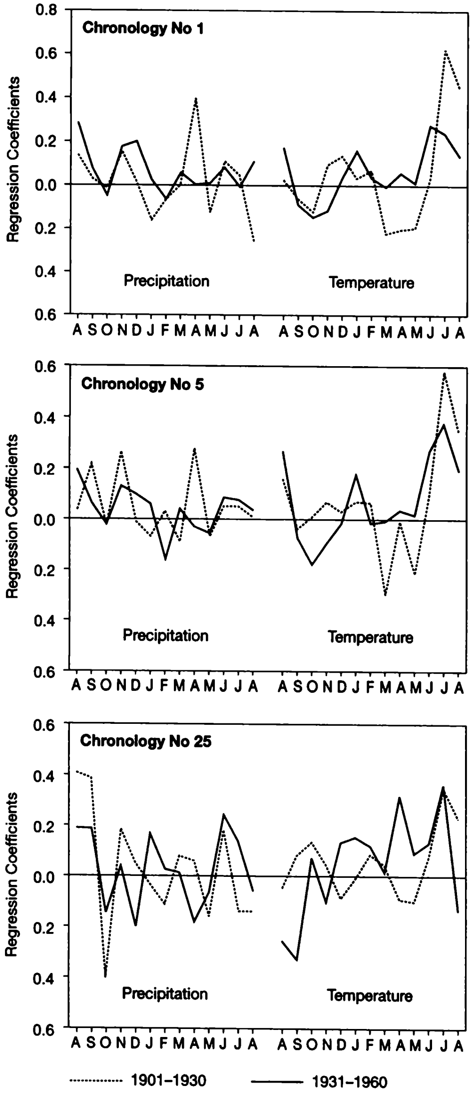

Figure 2 - Response functions for the larch chronologies 1 and 5 and for the spruce chronology 25.

both time intervals (r=0.52 and 0.47, b=0.53 and 0.24, respectively). Larch indices have a weak negative relation with October temperatures of the previous year (r=-0.14), and a positive one with January and February temperatures of the current year (r=0.26 and 0.13, respectively). The mean dispersion percent explained by temperatures of the 13 month period (from August of the previous year to August of the current year) is 50.1% (from 40 to 58%) for the larch chronologies and 48% for the spruce chronology.

Precipitation influences are much less than air temperature on the larch growth. The main contribution to the indices variability is August (r=0.36, b=0.23) and September (r=0.25, b=O.10) precipitation of the previous year. During the current years (from 1961), the relationship of the indices with August-September precipitation of the previous year has decreased in comparison with the previous time intervals. It is possible that this is related to an increase in precipitation during 1961 to 1989. The influence of November and December precipitation of the current year on tree growth is weak (r=0.20-0.24). There is higher correlation between the spruce indices and August-September precipitation of the previous year (r= 0.51 and 0.37, b= 0.34 and 0.19, respectively). The mean dispersion percent explained by temperature and precipitation from August of the previous year to August of the current year for the larch chronologies is 64.6% (from 56 to 73%). For the spruce chronology the value is 69%. The examples of relationships of larch and spruce growth indices with temperatures and precipitations of separate months are shown in Fig. 2.

In the various verification periods (1901-1930 and 1931-1960) there are differences in the growth response to climatic factors. The difficulties arise when all of the significant climatic variables are used to predict the growth indices based upon meteorological data. For example, using all of these variables in the calibration equation for 1931-

1960 of chronology 14, it suggests that the dispersion percent explained by climate is decreased from 84 to 14% during the verification period of 1901-1930. The majority of larch chronologies and spruce chronology show sufficiently stable relationships with June and July temperatures so as to allow the use of the period 1901-1960 for calibration (Table 2).

The stability disturbances of relationships are observed in the chronologies obtained in the snowy sites (plot 1). This is related to the low June temperatures during 1901-1930. In years with cold spring, the growing season begins much later (at the beginning of July) and June temperatures only slightly influence tree growth. During the present period (from 1961) June temperatures are close to those from 1901-1960 (4.9 and 5.2°C, respectively). In connection with this, the relationships between tree growth indices and June-July temperatures during the present period are similar to those which existed during the two verification periods (1901-1930 and 1931-1960) and the calibration period (1901-1960).

In order to reveal the similarities and differences between the actual and predicted growth indices during the period of possible influence of air pollutants (1961-1989), the following statistical characteristics are used: determination coefficients t-test, and sign test (FRITTS 1976). The differences between the actual and predicted growth indices are demonstrated in Fig. 3. These examinations have revealed that there are significant differences at the 95% level between the actual and predicted indices in most of the larch chronologies, especially on the t-criterion. There are no differences only in the larch chronology 8, obtained for the most remote plot (320 km). The stable differences between the actual and predicted indices are observed from the end of the 1960's (Fig. 3). The mean increment losses during 1961-1989 are in the order of 30-50%. The actual spruce indices were slightly lower in comparison with the predicted ones from 1961 to 1988. The tree increment analysis of the dead standing trees has shown that the dying-off of larch trees begins when the actual indices are more than 40% lower in comparison with the predicted ones.

Discussion

The data presented concerning the relationship of tree-ring indices with climatic characteristics has demonstrated that from 1901 to 1989 three periods (each 30 years long) can be identified, and each of them is characterized by the peculiarities of the impact of the climatic and anthropogenic factors on tree growth. The main difference between the time intervals of 1901-1930 and 1931-1960 consists of the following: during the first period, the contribution of June temperature was lower than that of August temperature, but was higher during the second period. This is caused by the very high year-by-year variability of June temperatures (from -0,6 to +12,0°C, Dudinka station). In this connection, there is an essential difference in the onset of larch growth which begins when the average daily temperature exceeds 5°C. In some years this happens at the end of June or at the beginning of July. The average June temperature in Dudinka during 1901-1930 was 1,8°C lower than that during 1931-1960 (4,3 and 6,1°C, respectively). In other words, during the colder period of 1901-1930, the season of tree growth has shifted to the later time period.

Years	Changes in number trees		Dead trees, number	Trees mortality % per year	Portion of dead standing trees to all trees, %
	living	dead standing			
		Plot 1			
Before 1925	89	16			15,2
1925-1929	89-88	16-17	1	0,22	16,2
1930-1934	88	17	–	–	16,2
1935-1939	88-87	17-18	1	0,22	17,1
1940-1944	87	18	–	–	17,1
1945-1949	87	18	–	–	17,1
1950-1954	87	18	–	–	17,1
1955-1959	87-86	18-19	1	0,22	18,1
1960-1964	86-85	19-20	1	0,24	19,0
1965-1969	85-84	20-21	1	0,24	20,0
1970-1974	84-81	21-24	3	0,72	22,9
1975-1979	81-76	24-29	5	1,24	27,6
1980-1984	76-67	29-38	9	2,36	36,2
1985-1989	67-50	38-55	17	5,08	52,4
		Plot 14			
Before 1970	44	6			12,0
1970-1974	44-41	6-8	2	0,90	16,0
1975-1979	42-39	8-11	3	1,42	22,0
1980-1984	39-28	11-22	11	5,64	44,0
1985-1989	28-18	22-32	10	7,14	64,0
		Plot 24			
Before 1970	114	11			8,8
1970-1974	114-113	11-12	1	0,18	9,6
1975-1979	113-110	12-15	3	0,54	12,0
1980-1984	110-102	15-23	8	1,46	18,4
1985-1989	102-90	23-35	12	2,36	28,0
		Plot 27			
Before 1970	44	9			17,0
1970-1974	44	9			17,0
1975-1979	44-43	9-10	1	0,46	18,9
1980-1984	43-37	10-16	6	2,80	30,2
1885-1989	32-37	16-26	10	5,40	49,1

Table 2 - The mortality dynamics of larch trees in the stands.

This explains why June temperature has made less of a contribution than August temperature to the tree growth variability in comparison with the warmer period of 1931-1960.

The radial growth of spruce trees begins 1-2 weeks later, and finishes earlier than larch tree growth. As a result, the influence of July temperature on spruce growth is highly expressed. The role of June tem-

Calibration period	1901-1930	1931-1960	1901-1960
Verfication period	1930-1960	1901-1930	
		Chronology 14	
Calibration			
R^2	0,37	0,52	0,44
Verification			
r^2	0,37	0,48	-
PMt	0,08	1,06	
Sign test			
+	21	22	
–	8	7	
		Chronology 1	
Calibration			
R^2	0,21	0,45	0,30
Verification			
r^2	0,14	0,20	-
PMt	1,73	0,12	
Sign test			
+	18	14	
–	11	15	
		Chronology 25	
Calibration			
R^2	0,23	0,28	0,30
Verification			
r^2	0,26	0,29	-
PMt	1,35	0,76	
Sign test			
+	23	23	
–	6	7	

R^2 square of the correlation coefficient calculated between actual and the estimated data; r^2 is the square of the actual/estimated correlation over the verification period; PMt is the t value derived using the product mean test, and sign test is a test for comparing the signs of the first differences for the estimated and actual data.

Table 3 - Examples calibration-verification statistics for June-July mean temperatures reconstruction model.

perature during cold years and periods effecting spruce growth is also decreased, but to a lesser extent than with larch growth.

Rather stable relationships between larch indices and August-September precipitation of the previous year are connected with the peculiarities of the water regime of soils in areas with permafrost. The supplement of available moisture in such soils takes place during the end of summer and at the beginning of autumn, when soils thaw to the maximum depth and when the quantity of precipitation is greatest

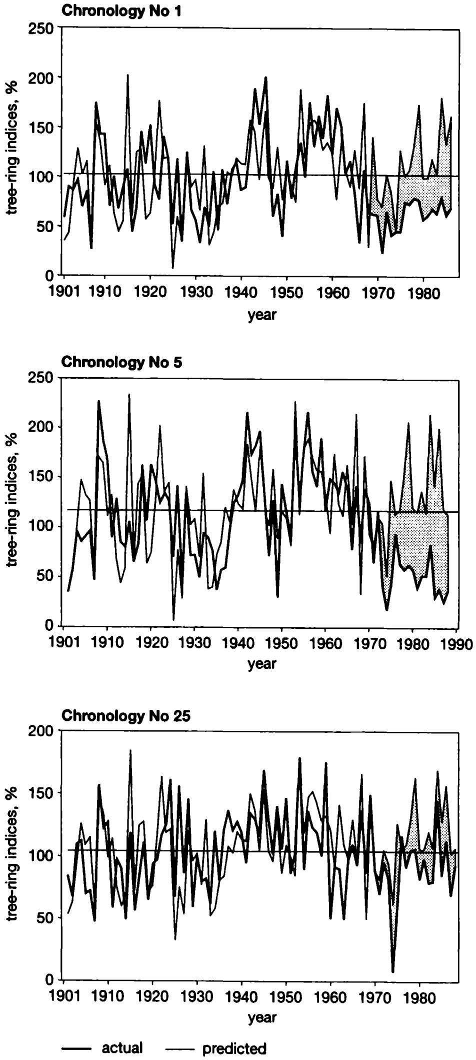

Figure 3. Actual and predicted growth indices for the chronologies no. 1, 5 and 25.

(Pozdnjakov 1975). In the Dudinka area during August and September, precipitation is more than 100 mm (this represents approximately 30% of the annual total). This moisture can be used by trees only during the next growing seasons. The significant and positive relationships between tree growth indices and June-July temperature in this area were also obtained by Simachev et alii (1992). However, we have not found the same significant and negative correlations between growth indices and June-July precipitation of the current year as they did. Besides, they have not rèvealed the connection between indices and August-September precipitation of the previous year as we did. Such differences may be a result of using the precipitation data of Dudinka station which has much shorter series of observation in comparison with Turukhansk station.

Prior to 1960, the variability of tree indices was mainly determined by the climatic factors. During the last 30 years a considerable weakening of the dendroclimatic relationships took place. There was a drastic decrease in tree growth, the appearance of many missing rings, a lowering of the sensitivity in annual tree growth, and a massive mortality of larch trees in the stands. These characteristics, in combination with progressing crown defoliation and dechromation, and the presence of the zonality with a various degree of forest degradation around the emission source, unequivocally indicates that the growth and state of the forests has been influenced by an additional factor, air contamination by sulphur dioxide.

As the main massifs of dead and damaged forest stands are placed to the south and south-east from the emission source, and the deciduous tree species were dying-off mainly, it follows that summer air emissions influence forests most of all (when the northern and north-western winds prevail). Siberian spruce suffers from pollutants much less than the larches and birch. Moreover, an intensive dying-off of larch and birch trees in stands has lead to the improvement of the radiation and thermal regimes for spruce, which usually grows in the secondary tree layer. The increment data for the last 30 years are confirmed by the fairly good state of spruce trees in this area, excepting the vicinities nearest the city of Norilsk.

The beginning of the actual growth decrease in comparison with the predicted growth began firstly in plot 6 situated at a distance of 30 km from Norilsk that additional connected with recreation around Talnach city. At the end of the 1960's, the intensive growth decrease started in the most plots (1, 5, 14, 24, 27 and 30), at a distance up to 100 km from the emissions source. A little later (at the beginning of the 1970's), the tree growth decrease began at a distance of 170 km (plot 7). The most significant decrease of larch growth (up to 80-90% from the expected values) took place in the low productive slope sites. The most productive forest stands, growing in the river valleys, have decreased radial growth to a lesser extent (20-50%).

The massive tree mortality began 10-15 years later than the observed decrease in tree growth. The visual damage signs (crown defoliation, and leaf dechromation) appeared about 10 years after the beginning of the growth decrease. Good ground exists to conclude that the tree-ring analysis is very realistic for early diagnostic of the forest states in the subtundra forests.

The observed data evidence a rather low stability of the subtundra open forests in relation to air pollutants in comparison with forests growing in the central and southern parts of taiga zone. This is due to the fact that tree vegetation grows here under the influence of adverse climatic conditions. Besides, high annual and many years climatic fluctuations are typical in this area, and these fluctuations can cause massive tree mortality during cold periods (SHIYATOV 1993).

At the beginning of the 1960's, when began the tree growth decrease near the city of Norilsk, under the influence of phytotoxic pollutants, climatic conditions were favorable for the existence of the tree vegetation. From the middle of the 1960's until the middle of the 1970's, the summer seasons were mainly cold and, from this time, the intensive forest degradation began. The quantity of the injurious emissions was comparatively small as during that period it was used a low sulfureous raw material for melting. The period of the maximum pollutants emission (1980-1985) coincided with the climatic period favorable for trees growth. That certainly promoted the increase in tree vitality. In the majority of the plots tree growth increased during this time. If during this period the temperatures of summer months were below the standard, the forest degradation would be more intensive. From the end of the 1980's, the next cold period began. Taking into account that in the nearest future the quantity of phytotoxic pollutants will be great, it can be expected that the intensive dying-off of forests will continue in this area. To diminish the catastrophic degradation of forests in future, it is necessary to decrease the emissions during the summer months.

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SUMMARY

The assessment of subtundra forests degradation by dendrochronological methods in the Norilsk industrial area

The study was conducted in the subtundra forests growing under the influence of air pollutants emitted from the Norilsk mining and metallurgical group of enterprises. Tree-ring data are used for a retrospective assessment of growth and state of forest stands. It was shown that the tree growth decrease began in the 1960’s, and massive tree mortality began 10-15 years later. The main factors which caused the intensive forest degradation are the influence of phytotoxic pollutants, basically sulphur dioxide, and the cooling in summer months from the middle of the 1960’s to the middle of the 1970’s.

RIASSUNTO

Valutazione del degrado della foresta della subtundra nell’area industriale di Norilsk mediante metodi dendrocronologici

Lo studio è stato condotto in soprassuoli di stazioni della subtundra, che risentono dei pollutanti prodotti nella regione industriale di Norilsk. Le cronologie anulari sono state qui utilizzate per valutare sia lo stato dei soprassuoli sia l’andamento dell’accrescrimento negli anni passati. Si è visto che l’accrescimento comincia a diminuire dopo il 1960 e

che la mortalità delle piante assume valori elevati dopo 10-15 anni. I fattori principali, che determinano il deperimento dei soprassuoli, sono i pollutanti fitotossici a base di biossido di solfo e l'abbassamento delle temperature dei mesi estivi durante il decennio 1965-1975.

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