ISSN 1995-4255, Contemporary Problems of Ecology, 2014, Vol. 7, No. 7, pp. 759–769. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © T.V. Chernen'kova, Yu.N. Bochkarev, M. Friedrich, T. Boettger, 2012, published in Lesovedenie, 2012, No. 4, pp. 3–15.

The Impact of Natural and Anthropogenic Factors on Radial Tree Growth on the Northern Kola Peninsula

T. V. Chernen'kova[a], Yu. N. Bochkarev[b], M. Friedrich[c, d], and T. Boettger[e]

[a] *Research Center for Ecology and Productivity of Forests, ul. Profsoyuznaya 84/32, Moscow, 117997 Russia*
[b] *Depatment of Geography, Moscow State University, Moscow, 119992 Russia*
[c] *Institute of Botany, Hohenheim University, Garbenstraβe 30, Stuttgart, 70599 Germany*
[d] *Heidelberg Academy of Sciences, Karlstr. 4, Heidelberg, 69117 Germany*
[e] *Helmholtz Centre for Environmental Research—UFZ, Department of Catchment Hydrology, Theodor-Lieser-Str. 4, Halle, D-06120 Germany*
e-mail: chernenkova50@mail.ru

Received January 30, 2012

Abstract—The dynamics of radial growth of pine (*Pinus sylvestris* L.) and spruce (*Picea obovata* Ledeb.) trees at the northern limit of their distribution in the area of the Kola Peninsula affected by emissions from the Severonikel industrial complex has been investigated. A correlation between the radial growth of trees and a combination of environmental factors has been revealed through the use of statistical methods, and a contribution of individual factors has been identified. Statistically significant correlations between the productivity of trees, on one hand, and the level of pollution, topography, and climatic effects, on the other, have been detected. A significant correlation between the degree of tree growth and the amount of industrial emissions in the atmosphere has been revealed; the correlation depended on the degree of technogenic impact on the trees, the tree species, and the location of trees on hill slopes. The growth oscillations of different frequencies (long waves of 50 years, medium-length waves of 30 years, and short annual waves) were shown to depend on climatic factors in different ways.

Keywords: dendrochronological methods, pine, spruce, northern Kola Peninsula, air pollution, heavy metals, annual growth, climate, landscape factors

DOI: 10.1134/S199542551407004X

INTRODUCTION

The impact of extrinsic environmental factors on coniferous trees is most evident when trees growing close to the distribution border are considered [11]. The Kola Peninsula is one of such areas; notably, Severonikel Mining and Metallurgical Complex (MMC), a source of strong chronic pollutant emissions, is found in the center of the peninsula. Numerous examples of damage to trees surrounding Severonikel MMC have been extensively reported [1, 8, 10, 13, 20].

The dendrochronological method is often used for the assessment of changes in environmental conditions, including the dynamics of climate and weather factors [2–4, 12, 16, 21], and for evaluation of functional disorders evoked by technogenic influence [6, 9]. Statistical methods reveal a correlation between radial tree growth and a combination of simultaneously acting environmental factors and make it possible to assess the individual contribution of every factor; however, there are a limited number of studies addressing the multifactorial determination of the structural and functional characteristics of forest stands in specific areas [15, 25]. However, a Canadian research group [23] stated that the use of dendrochronological and statistical methods has considerable potential for understanding the short-term responses of boreal forest productivity to environmental conditions and for assessing the impact of this phenomenon on the carbon balance. The use of a mixed-effects model resulted in the demonstration of a steady decline in the radial growth of common pine trees in Northern Eurasia; the growth decreased by 17%, or 0.0025 mm year^{-1}, between the 1930s and the 1980s [23].

The goal of the present study was to analyze changes in the radial growth of pine (*Pinus sylvestris* L.) and spruce (*Picea obovata* Ledeb.) on the Kola Peninsula that were causeed by atmospheric pollution, habitat status, and climatic parameters.

MATERIALS AND METHODS

The study area is located inside the Arctic Circle in the northern taiga subzone in the central part of Kola Peninsula and mostly covered by sparse spruce and pine shrub-green moss forests. The study area is

Table 1. Characteristics of sampling sites

Zone	Direction and distance from the combine, km	Altitude above sea level, m	Slope exposure	Tree species	Longitude	Latitude
Impact	S-5	<250	E	S	32.7848	67.9082
	S-10	250–300	E	S	32.7867	67.8464
		<250	n/d	P	32.7066	67.8543
Buffer	S-20	<250	NE	S	32.7997	67.7611
		250–300	ENE	S	32.7717	67.7640
		>300	n/d	S	32.7480	67.7619
	S-30	<250	NNW	S	32.8025	67.6792
		250–300	ESE	S	32.7924	67.6707
		>300	E	S	32.7846	67.6721
		<250	N	P	32.7720	67.6473
		<250	NW	P	32.74983	67.6498
Background	S-65	<250	NE	P	32.51450	67.5707
		<250	NE	P	32.50833	67.5745
		<250	NE	P	32.49250	67.5790
Control	NW-70	<250	NE	S	31.0851	68.2291
		250–300	E	S	31.0247	68.2282
		250–300	n/d	S	31.0307	68.2283
		250–300	E	S	31.0609	68.2287
		250–300	E	S	31.0670	68.2287
		250–300	E	S	31.0730	68.2280
		>300	NE	S	31.0187	68.2282
		>300	W	S	31.0368	68.2284
		>300	W	S	31.0420	68.2284
		>300	E	S	31.0549	68.2289
	SE-70	>300	E	P	34.1463	67.7398

E—towards east, N—towards north, W—towards west, n/d—not defined.

located at an altitude of 100–1200 m above sea level. The average annual sum of the active average daily air temperatures exceeding 10°C in the area equals 900°C, and the annual precipitation is 500–600 mm [7]. Severonikel Mining and Metallurgical Complex (MMC), a source of air pollution, is located in the study area; it has had a definitive effect on the appearance and status of forest ecosystems in the vicinity of the town of Monchegorsk since 1935. Heavy metals and sulfur compounds have been the main environmental pollutants of the area surrounding the MMC for decades. The volume of industrial emissions into the atmosphere in 1980 (in tons years^{-1}) was as follows: sulfur dioxide was 220000–240000; nickel compounds were 3400; copper compounds were 2640, cobalt compounds were 100; nitrogen oxides were 1200, sulfuric acid (vapors) was 3350, chlorine was 1000, and fluorides were 800. The emissions have decreased significantly in recent years due to a decrease in production volumes; for instance, the emissions of SO_2 decreased more than sixfold and were close to 35.9 t year^{-1} in 2007 [5].

The status of pine and spruce tree stands was evaluated at test sites in pine and spruce communities belonging to the northern boreal forest zonal type (Piceeta fruticuloso-hylocomiosa and Pineta fruticuloso-hylocomiosa + Pineta hylocomioso-cladinosa). The gradient of pollution was most pronounced in the meridional direction, in accordance with the wind rose in the area, and therefore test sites were established at different distances from the emission source within areas of digression characterized by varying degrees of biocenosis disturbance (Table 1, Fig. 1). Plant communities located outside the zone of technogenic impact, about 70 km to the northwest (northwestern border of Lapland Reserve) and southeast (eastern Khibiny) from the plant, were used as controls. Radial growth values for pine and spruce were compared for trees growing under similar ecotopic conditions and comparable technogenic loads at an altitude of 250–300 m above sea level, namely S11 (pine) was compared to S10 (spruce); S30 (pine) was compared to S30 (spruce), and SE70 (pine) was compared to NW-70 (spruce).

Wood sampling and methods of measurement of annual rings. Test sites for the assessment of the effect of habitat (primarily relief) variability on the productivity of the tree stand were set up on landscape profiles at altitudes less than 250 m, 250–300 m, and more than 300 m above sea level within each zone of digression and in control areas. The zone closest to the MMC formed an exception, because no trees survived at altitudes exceeding 300 m above sea level in ecosystems disturbed to the maximal degree. The age of trees and the value of radial growth were determined for trees exceeding 10 cm in diameter by taking two wood samples on opposite sides of the tree trunk with a wood borer. Fifteen to twenty tree trunks were measured at every altitude for every test site; samples were obtained from both living and dead trees. A total of 70 spruce trunks and 40 pine trunks were measured at medium heights.

The width of tree rings was measured using the semi-automatic LINTAB 5 complex and the TSAP WIN software package. Cross-dating and building of chronologies of growth indices at test sites was performed using the TSAP WIN software package and ARSTAN software from the DPL library of dendrochronological software [24]. COFECHA software was used to verify the cross-dating. The regional chronology of living trees was a part of the cross-dating used to determine the years of growth and dates of death for trees that died as a result of air pollution. The chronology for pine trees from the Khibiny Mountains [22] and Finnish Lapland [19], among others, was used. Age-related trends were eliminated using the regional curve (RCS) method, the method of averaging of indexed series [18], and the selection method of cubic splines for the detection of low-frequency components of the growth series [17].

Chemical analysis of soil and plant samples. A standard atomic absorption spectrophotometry procedure for the assessment of total metal content (1983) and X-ray fluorescence spectroscopy on a PicoTAX TXRF spectrometer (Bruker AXS, Germany) were used to assess the level of contamination. The lowest limits of detection (LLD) were $5–10 \times 10^{-12}$ g L^{-1} or g kg^{-1} (2008, 2009). Quantitative analysis of plant and soil samples was carried out using an internal standard (namely, gallium nitrate, State standard sample of aqueous solution, certificate number 1543 GDVI 410408.024PS, GSO 7340-96), that was added to each sample.

Climatic characteristics. A synthetic temperature series constructed from reports by three weather stations (Khibiny, Apatity, and Kola) spanning the years 1878–2005 was used; the method for series calculation was reported in detail by Kononov et al. [22]. The

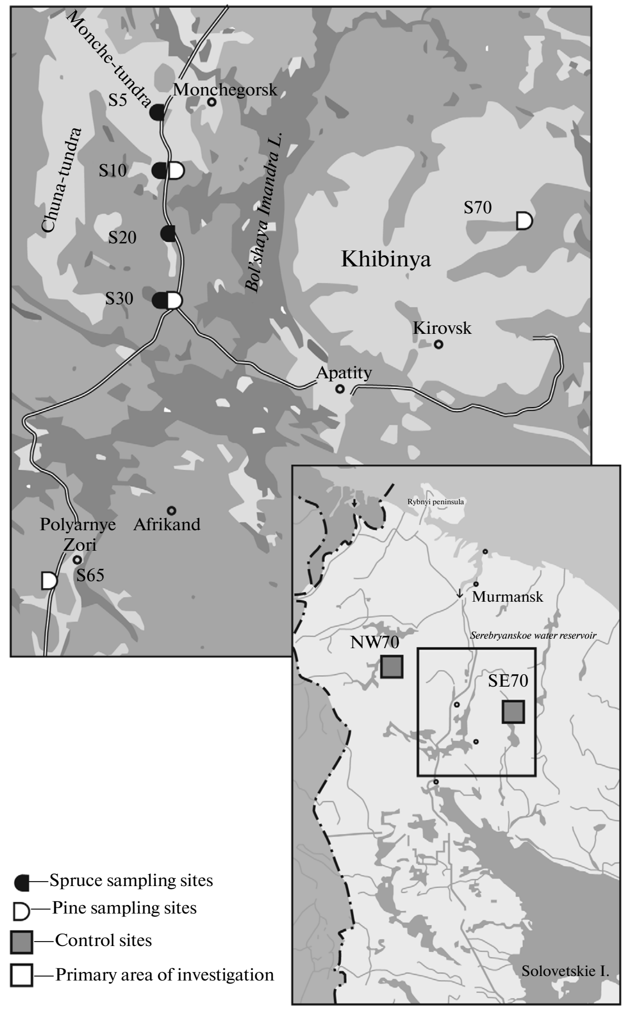

Fig. 1. Schematic map of the location of study sites and conventional zoning of the area.

average correlation coefficient of monthly average temperatures measured at these three stations was 0.990 ± 0.005. The following series of climatic parameters were selected as independent variables: average temperatures and rainfall from April to August, April–May, May–June, June–July, and July–August of the current and the previous year, from September to November, September–October, October–November of the previous year, as well as the average summer temperature and rainfall of the current and the previous year, the average winter temperature and precipitation (in November and December of the previous year and from January to March of the current year), and the average annual temperature and precipitation from September to December of the previous year and from January to August of the current year.

Statistical analysis. Joint analysis of chronological graphs of annual growth superimposed with smoothened curves (cubic splines) and multiple stepwise regression were used [14].

Table 2. Changes in the concentration of copper and nickel in different parts of pine trees and in the soil in the vicinity of the Severonikel' metallurgical plant, mg kg^{-1} (data from 1983, 2008, and 2009)

Object	Distance to the emission source, km				
	5	10	20	30	70 (control)
Cu					
Needles					
current year	31.2	101.3	49.6	17.6	7.4
1st year ≥	100.8	294.2	72.8	32.9	7.3
2nd year ≥	92.0	120.5	48.0	38.2	10.4
Wood	4.2	5.3	4.1	2.0	1.8
Roots	145.0	79.3	35.8	5.1	2.8
Ni					
Needles					
current year	188.9	214.0	101.4	20.0	5.8
1st year ≥	870.3	203.9	139.2	20.6	9.5
2nd year ≥	866.0	250.0	61.2	18.4	11.6
Wood	5.0	6.2	3.1	1.2	0.4
Roots	235.7	130.1	85.3	15.2	3.1
Cu					
Litter (OF)	22857/3383*	673.6/4588*	51.7/1293*	45.5/741*	3.25
Soil (E)	114.0/47.0*	32.5/62.0*	5.3/10.5*	3.1/9.8*	1.47
Ni					
Litter (OF)	6220.4/4819*	2068.4/5600*	332.1/1547*	115.4/922*	4.5
Soil (E)	424.5/181*	89.6/136*	14.6/43.0*	3.3/26.0*	0.33

* Data of 2008 and 2009.

RESULTS AND DISCUSSION

The metallurgical complex has been releasing toxic substances into the atmosphere for decades, and this had a decisive effect of the accumulation of toxic compounds in the biotic and abiotic components of the environment in areas surrounding the production facilities. The concentrations of contaminants in different part of pine trees, soil, and litter sampled near the MMC in the 1980s were almost two orders of magnitude higher than the respective values for uncontaminated areas and equaled threshold values for plant growth. Analysis of soil samples collected at the same test sites in 2008 and 2009 revealed elevated levels of many elements, including copper and nickel; the pollution levels were generally higher than those reported in the 1980s (Table 2). This confirmed the propensity of heavy metals to accumulate in ecosystems over time and thus exert prolonged effects on living organisms, even in case of a reduction or complete elimination of continued technogenic loading.

Analysis of dendrochronological parameters allowed for the assessment of changes in the growth of trees in the area exposed to emissions from the metallurgical complex. Curves illustrating the changes of growth ring indices for pine and spruce trees from areas with different degrees of contamination are shown in Figs. 2a and 2b. The chronologies of spruce and pine trees were apparently well synchronized with each other, as well as with average summer temperature, before the 1970s. Afterwards, the asynchrony of the curves became evident. The character of asynchrony differs between tree species and zones of contamination. For instance, a sharp increase of the technogenic load in the 1970s resulted in a dramatic decrease in spruce growth in the contaminated area (at distances of 10 and 20 km), although the growth of trees in the control and buffer zones became more intensive. Spruce trees in the impact and buffer zones closest to the plant grew extremely slowly in the years 1982–1993 because of increasing contaminant levels, both in the atmosphere and in the soil, and low temperatures (0.65°C lower than the average temperature for the years 1878–2007 equal to 12.8°C). A considerable reduction in the airborne industrial load in the early 1990s caused an increase in the radial growth of spruce trees within 30 km of the metallurgical plant.

Analysis of the pine growth chronology revealed an increase in tree growth after 1940. Growth in all areas was inhibited to a certain extent in the 1970s; this may be a consequence of the preceding cold period, dra-

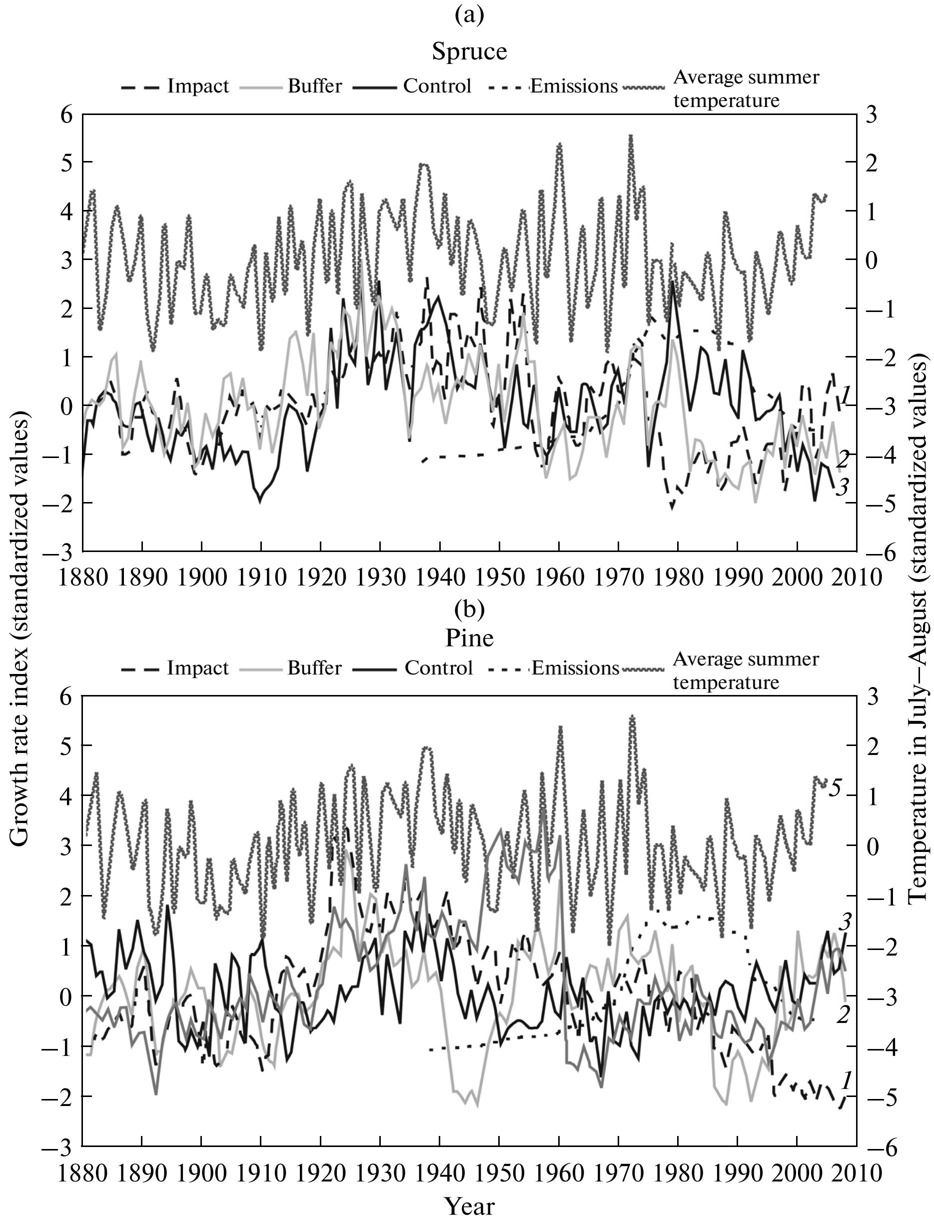

Fig. 2. Changes in annual radial growth of trees in areas with different degrees of pollution; (a) spruce in impact (S10), buffer (S20 and S30), and control (NW70) zones; (b) pine in impact (S11), buffer (S30), background (S65), and control (SE70) zones.

matically increased industrial emissions, or the combined effect of both factors (Fig. 2b). The inhibition of pine growth in the impact zone (11 km) was primarily manifested as a decrease in annual oscillations (relatively to the control zone, for example) and was evident already in the 1930s. The curve generally follows the temperature variation until 1980, although the variation was less pronounced than in other locations. A sharp decrease in annual growth was observed at distances of 11 and 30 km after 1980; the decrease at the latter distance stopped in 1990, while at the former distance it continued. In contrast to spruce, pine trees in the impact zone did not show an increase in annual growth after the decrease of the emission level in the 1990s but instead showed a continued sharp decrease.

The difference of the annual growth of trees from polluted and control habitats was plotted on graphs for a reliable assessment of the effect of air pollution on growth dynamics (Figs. 3a and 3b). The graph for spruce trees from the impact zone shows that the differences were negative during the period when the emissions were maximal (the 1980s) and became positive when the production volumes decreased and growth was restored. The periods during which the differences were positive and negative are shifted by approximately ten years for the trees of the buffer

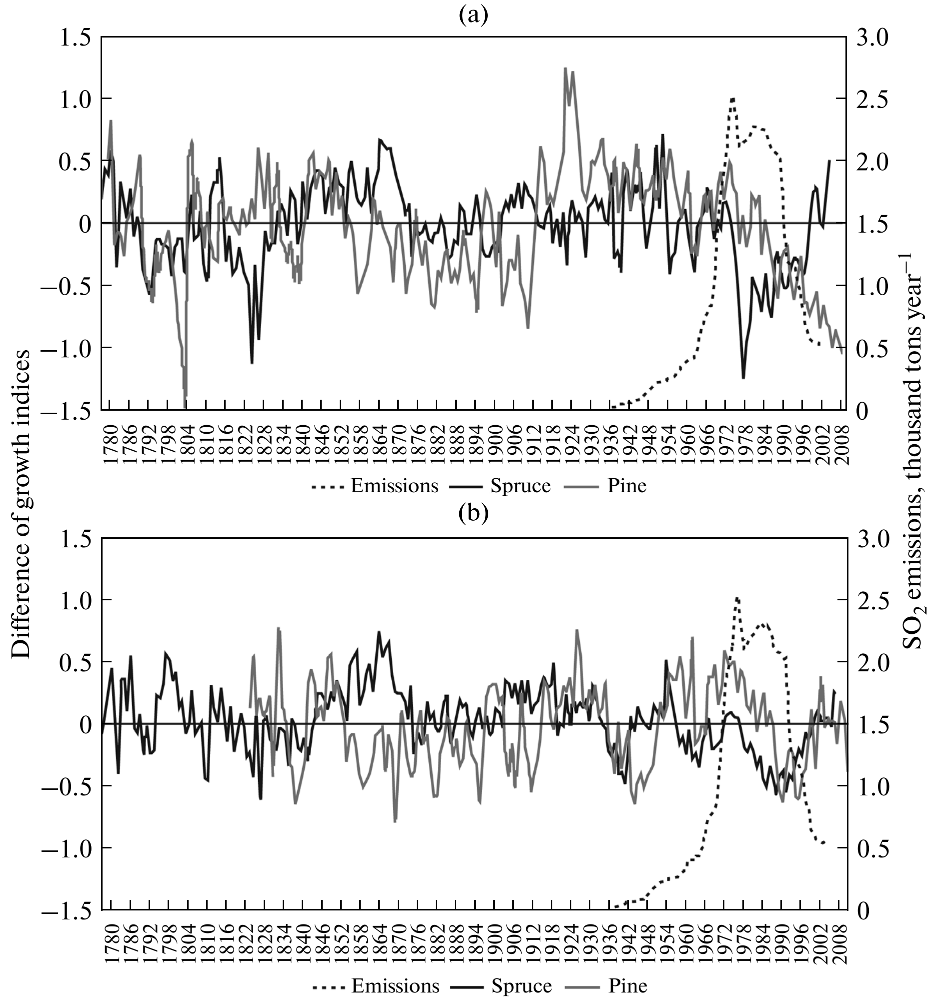

Fig. 3. The difference in growth rates of pine and spruce from polluted and control areas: a—difference between impact and control zones; b—difference between buffer and control zones.

zone. Pine trees growing in the impact zone demonstrated negative differences even after the emission volumes decreased, in contrast to spruce from the same zone, while the curves for both tree species from the buffer zone were identical and well synchronized. Thus, pine trees growing in the impact zone (10–20 km from the plant) showed a reaction to technogenic loads—that is, a clear decrease in the general intensity of annual growth oscillations—starting from the 1930s. The change in radial growth of pine trees in the zone of maximum contamination was sharper than that for spruce; moreover, the annual radial growth of pine trees continued decreasing after a significant reduction of emissions into the atmosphere, while spruce demonstrated a capacity for restoration of the preindustrial growth rate.

A comparison of all chronologies for both tree species starting from the mid-18th century reveals considerable synchrony, which is mostly due to the effects of the average summer temperature, as inferred from climatic data available from 1878 only. However, data from recent years revealed asynchrony between the growth of control spruce trees and the temperature trend (average temperature in July and August), while the radial growth of pine showed a reliable positive correlation with the temperature trend (R = 0.62) (Figs. 4a and 4b).

The detection of a correlation between tree productivity and climatic factors of different hierarchical levels was based on regression models (multiple stepwise regression). Long-wave oscillations (about 50 years or longer) were less strongly correlated with the temperature dynamics than the short-wave oscillations (about 30 years), as is evident from the significantly higher coefficient of correlation between growth and climatic parameters for the latter type of oscillations (R = 0.56 versus R = 0.52 for the long-wave oscillations). The maximal correlation with climatic parameters (R = 0.60–0.73) was detected for the interannual hierarchical level, both before and after the beginning of intense operation at the metallurgical plant. Weakening of the correlation to climatic param-

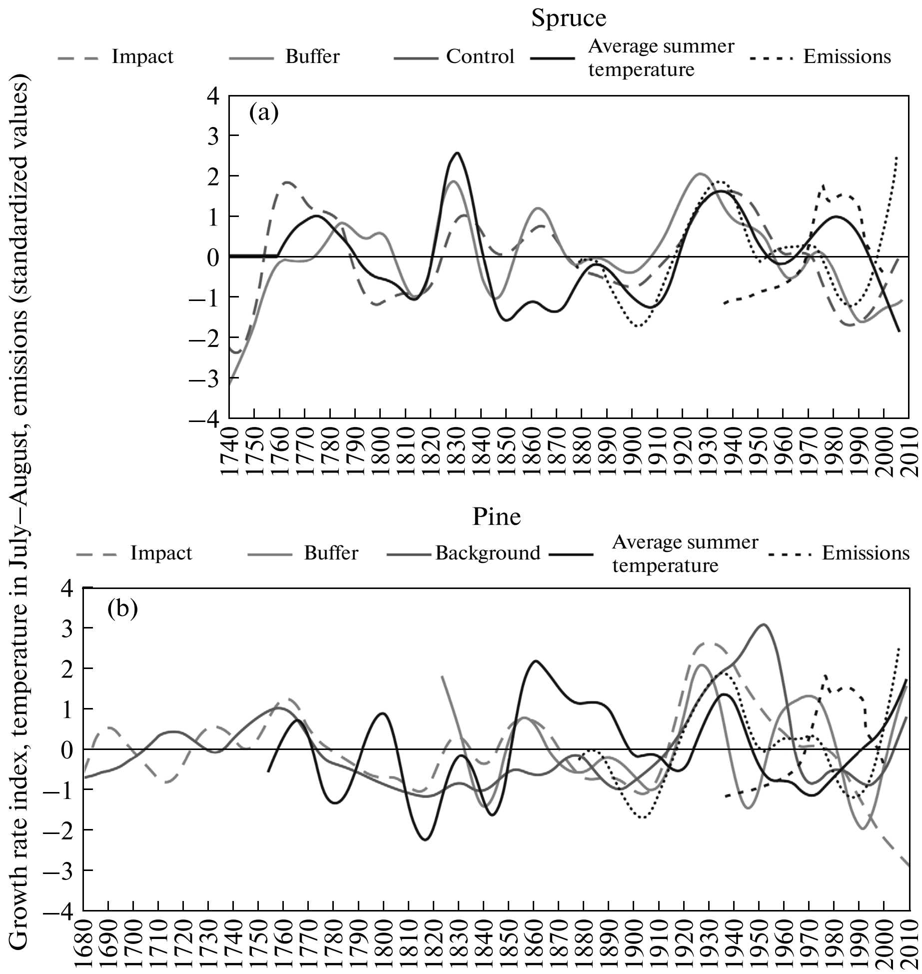

Fig. 4. Changes in average growth indices for spruce (a) and pine (b) (smoothened curves), average summer temperature, and emissions of SO_2 into the atmosphere (thousand tons year-1) (standardized curves).

eters upon the decrease of oscillation frequency is evident of a more significant contribution of the intrinsic developmental processes in the ecosystem to growth oscillations at higher hierarchical levels, although the effect of temperature fluctuations on long-wave oscillations cannot be denied, since the temperature and growth rate curves are apparently synchronized to a considerable extent (Figs. 2 and 4).

The constructed regression models were used to analyze the composition of the set of climatic variables determining the growth of trees. The analysis revealed a statistically significant correlation both with general climatic variables (average temperature in July–August, October temperature, November temperature, and precipitation in October) and with specific variables determining the growth of trees near the source of emissions (Table 3). The average summer temperature, for instance, had a direct significant positive impact on annual growth. The effect of October temperature and precipitation was positive as well, while a negative effect was obvious in the case of November temperature in the year preceding the year in which the growth was measured (conditions of soil freezing and snow layer formation). It was also negative for summer precipitation, since the area under investigation receives excess water. The sum of winter precipitation exerted a strong influence of the opposite sign as well. Importantly, the correlation between growth and climatic parameters for both pine and spruce growing in the impact zone (10 km) was significantly higher prior to the beginning of industrial operation than after it. This shows that the conditions for the growth of trees near Monchegorsk were initially more extreme than in the other areas, presumably as a result of orographic conditions, since the dependence on climatic parameters is more pronounced for trees growing under less favorable conditions.

Separate chronologies were constructed for spruce trees growing at different altitudes, namely, below 250, 250–300, and above 300 m above sea level, in order to reveal the effect of landscape factors on the dynamics of growth; certain changes in the radial growth were detected (Figs. 5a–5c). The amplitude of growth oscillations was notably smaller for trees growing at

Table 3. Coefficients for the independent variables in regression models for spruce with the industrial period taken into account

Climatic variables	Prior to the industrial period (1878–1974)			Full range (1878–2007)		
	control	buffer	impact	control	buffer	impact
Temperature, May, current year		–0.17613	–0.16151			
Temperature, April, previous year					0.222837	
Temperature, May, previous year			–0.31013		–0.23469	–0.30582
Temperature, June, previous year			0.183778			
Temperature, July, previous year	–0.18471					
Temperature, August, previous year		0.162145	0.267987			0.274472
Temperature, September, previous year	0.183078			0.238746		
Average summer temperature, previous year	0.28197	0.423344	0.425926	0.476888	0.285356	0.312848
Average annual temperature, previous year			0.261899			0.168369
Average annual temperature, previous year			0.274455			0.170521
Precipitation, April, current year				–0.18388		
Precipitation, July, current year						–0.19465
Precipitation, August, current year						0.165131
Precipitation, April, previous year			–0.15946			
Precipitation, August, previous year			0.182569			
Precipitation, October, previous year			0.213938	0.246207		
Average winter precipitation (November and December, previous year, and January–April, current year)	–0.16837	–0.18539			–0.30724	–0.12681
Average annual precipitation (September–December, previous year, and January–August, current year)	–0.22565		–0.28984			
R—multiple regression coefficient	0.48	0.52	0.73	0.55	0.51	0.73
F-value, Fisher's test	4.64	8.9781	8.2298	6.5869	6.4584	7.9168
Significance level for Fisher's test	$p < .00037$	$p < .00000$	$p < .00000$	$p < .00004$	$p < .00016$	$p < .00000$

more than 300 m above sea level. On the other hand, the increase in growth after the 1990s, when the emissions of the metallurgical plant decreased, was more pronounced at altitudes below 250 m than at higher levels. The differences in the dynamics of tree recovery can be due to more favorable environmental conditions at the lower geomorphological level, such as lower erosion intensity and higher accumulation intensity, which provide for the formation of a thick organogenic soil horizon, higher productivity of the ecosystems in the lower positions, and a higher resistance to pollution as well.

Differences in the position of the trees along the height of the slope affected the character of the dependence of radial growth on climate. The dependence was most pronounced at the medium altitude level (250–300 m) for both the impact and control zones; the average multiple correlation coefficient equaled 0.62, while for altitudes below 250 m it equaled 0.49, and for altitudes above 300 m it equaled 0.52. The reasons for this may be a greater intensity of intrinsic developmental processes in the ecosystem at the lower level and stronger exogenic geomorphological processes and winds (not directly related to the climatic features under consideration) at the higher level. However, the climate dependence was pronounced in all oscillation frequency ranges (low, medium, and high) at both the high (over 300 m above sea level) and medium altitude levels (the average multiple correlation coefficient equaled 0.57), which is evident of the increased sensitivity of trees exposed to technogenic stress due to industrial emissions. The climate dependence of growth was minimal for all hierarchic levels of oscillations, since trees growing at altitudes below 250 m within 10 km from the metallurgical plant were considered (the multiple correlation coefficient was 0.39 on average). This may be due to a decrease in habitat pessimality in the lower parts

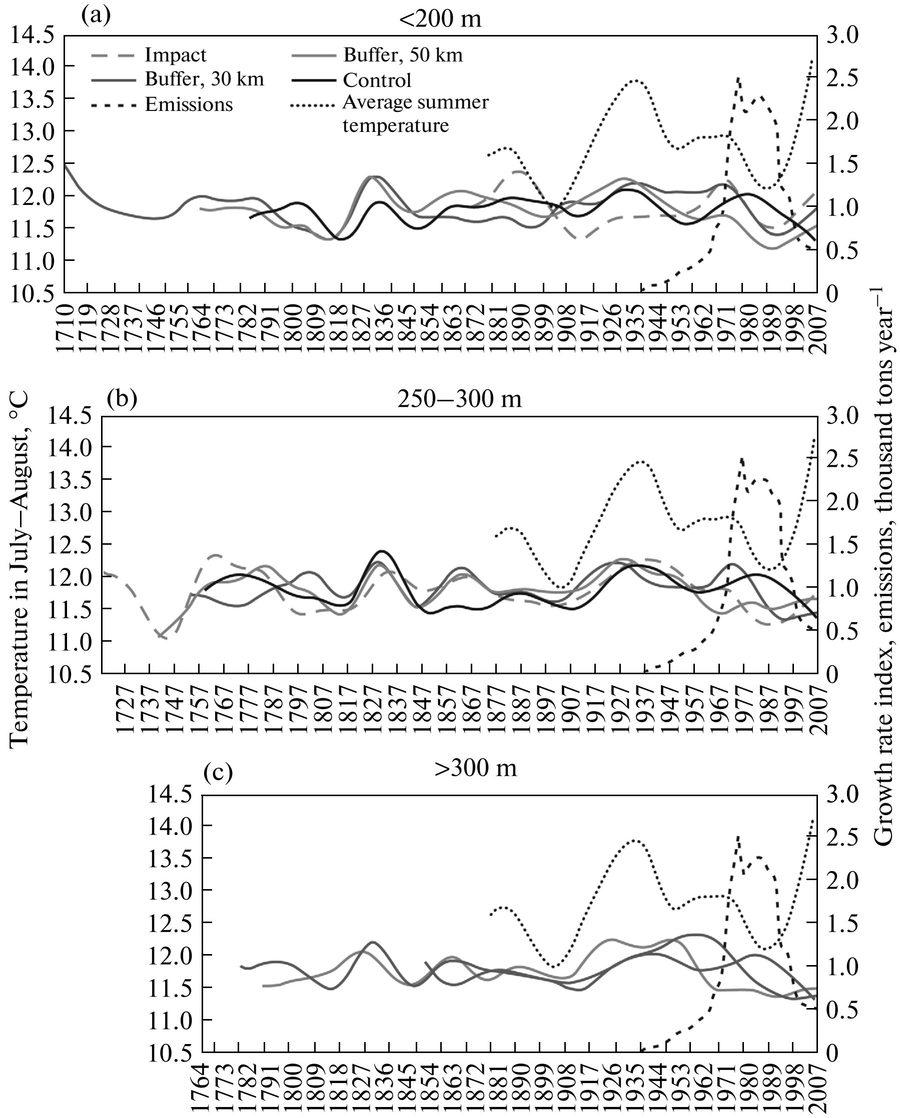

Fig. 5. Changes in annual radial growth of spruce trees in different locations within the relief in impact (5 and 10 km), buffer (20 and 30 km) and control zones.
(a) Below 250 m; (b) 250–300 m, and (c) above 300 m above sea level.

of the slope, which promotes a higher resistance of spruce to climatic effects.

The negative impact of average winter precipitation was specific for trees growing at medium and low altitudes within 30 km of the plant; this was due to prolonged snow thawing and excess soil moisture, promoting a delay in vegetation; this delay did not occur at the top border of the forest (above 300 m) because of blowing snow. The temperatures in May also had a negative effect on the trees in the aforementioned areas, since very early thawing of the snow resulted in soil freezing during the return of cold weather when the trees were beginning to awaken, and the area close to the production plant was devoid of peat litter protecting the soil from freezing.

CONCLUSION

Analysis of the factors affecting tree stand productivity simultaneously demonstrated the significant impact of the technogenic factor in the area under investigation and a climatic component limiting the expansion of forest communities towards the north. A significant correlation between tree growth and the volume of atmospheric emissions was revealed; the correlation was nonlinear and depended on the volume of technogenic load on trees growing at different distances from the plant, on the tree species, and on the location of trees on hill slopes. It is notable that differences in the response of spruce and pine trees to technogenic stress were revealed. Notwithstanding the substantial reduction of emissions in the recent years,

Table 4. Coefficients for the independent variables in regression models for pine with the industrial period taken into account

Climatic variables	Prior to the industrial period (1878–1974)			Full range (1878–2007)		
	control	buffer	impact	control	buffer	impact
Temperature, May, current year				0.268601		
Temperature, June, current year						–0.300747
Temperature, July, current year		0.183697	0.156031			
Temperature, August, current year		0.260915				
Temperature, August, previous year			0.248813			
Temperature, September, previous year			0.237481	0.210090		0.271515
Temperature, October, previous year						
Temperature, November, previous year			0.204386			
Average annual temperature, previous year	0.172212	0.339942			0.275554	0.598766
Average winter temperature, previous year						0.186827
Average summer temperature, previous year						0.240991
Precipitation, July, current year			–0.343594			
Precipitation, June, previous year			0.155211			
Precipitation, October, previous year	–0.169665			–0.415551		
Average annual precipitation (September–December, previous year, and January–August, current year)			0.389523			
Average winter precipitation (November and December, previous year, and January–April, current year)			–0.179401			
Average winter precipitation, previous year			–0.239698	–0.195473		
R–multiple regression coefficient	0.44	0.45	0.71	0.56	0.38	0.68
F-value, Fisher’s test	4.1629	4.4024	7.5254	5.3501	4.2538	8.3312
Significance level for Fisher’s test	$p < .00088$	$p < .00054$	$p < .00000$	$p < .00014$	$p < .00795$	$p < .00000$

the extent of radial tree growth in the polluted area remained significantly lower than the control and background values. The main reasons for this are the high content of heavy metals in the organogenic horizons of the soil and the persisting influx of contaminants from the atmosphere.

Comparison of all of the chronologies for both tree species starting from the mid-18th century reveals considerable synchrony, which is mostly due to the effect of the average summer temperature (as inferred from climatic data available for 1878 and later). The heat factor was more significant for spruce growing in the region than the precipitation factor; this is in accordance with Liebig’s law of limiting factors, since the sum of positive temperatures is minimal for the area. Differences in the altitude of tree growth on hill slopes determined the differences in the character of correlations between radial growth and climatic factors. The correlation was maximal for the medium altitude level, both in the impact zone and in the control zone. The effect of the metallurgical plant on spruce growth dynamics was less pronounced for the lowest geomorphological level than for the middle and upper levels.

Different characters of dependence on climatic factors was demonstrated for the growth rate oscillations of different hierarchical levels (long-wave oscillations of 50 years, medium-wavelength oscillations of 30 years, and short interannual oscillations). The maximal correlation with climatic parameters was demonstrated for the interannual hierarchical level, both before the beginning of intensive industrial operation and after it. Weakening of the correlation to climatic parameters concomitantly to the decrease in oscillation frequency is indicative of a more significant contribution of the intrinsic developmental processes in the ecosystem to oscillations of higher hierarchical levels.

An attempt to consider and distinguish the effects of several factors on tree growth showed that finding a solution for this task is feasible, notwithstanding the complexity of the task. As a result, the significance of a range of environmental factors for the production processes in coniferous forests was estimated; failing to take these findings into account could have led to misinterpretation of the obtained data.

ACKNOWLEDGMENTS

This work was supported by the program of the Presidium of Russian Academy of Sciences to develop a methodology for monitoring of forest biodiversity and the Russian Foundation for Basic Research, grant nos. 11-04-01093 and 07-04-01743.

REFERENCES

1. Alekseev, A.S., Fluctuations of radial increase in woods affected by air pollution, *Lesovedenie*, 1990, no. 2, pp. 82–86.
2. Bitvinskas, T.T., *Dendroklimaticheskie issledovaniya* (Dendroclimatic Studies), Leningrad: Gidrometeoizdat, 1974.
3. Vaganov, E.A., Registration of warming in current century by the cells of annual tree rings, *Dokl. Ross. Akad. Nauk*, 1996, vol. 351, no. 2, pp. 281–283.
4. Vaganov, E.A. and Shiyatov, S.G., Dendroclimatic and dendroecological studies in Northern Eurasia, *Lesovedenie*, 2005, no. 4, pp. 18–27.
5. The Data of the Kola Mining-Metallurgy Company. http://www.kolagmk.ru/rus/ecology/
6. Musaev, E.K., Seasonal growth and structure of annual rings of Scots pine after Chernobyl disaster, *Lesovedenie*, 1996, no. 1, pp. 16–28 .
7. *Spravochnik po klimatu SSSR. Murmanskaya oblast'* (Handbook on Climate in USSR. Murmansk Oblast), Leningrad: Gidrometeoizdat, 1965, 1966, 1968, no. 2.
8. Tsvetkov, V.F. and Tsvetkov, I.V., *Les v usloviyakh aerotekhnogennogo zagryazneniya* (Forest in Conditions of Air Industrial Pollution), Arkhangelsk: Arkhan. Tsentr Russ. Geogr. O-va, 2003.
9. Chernen'kova, T.V., Basova, E.V, Bochkarev, Yu.N., and Puzachenko, M.Yu., Analysis of biodiversity of forests in the zone affected by Severonikel Mining and Smelting Company, *Lesovedenie,* 2009, no. 6, pp. 38–45.
10. Chernen'kova, T.V. and Makarov, A.V., Growth of Scotch pine in neighborhood of Severonikel Mining and Smelting Company, *Lesovedenie*, 1996, no. 5, pp. 72–76.
11. Shiyatov, S.G., *Dinamika drevesnoi i kustarnikovoi rastitel'nosti v gorakh polyarnogo Urala pod vlyaniem sovremennykh izmenenii klimata* (Dynamics of Wood and Scrub Vegetation in Mountains of Polar Ural Affected by Climate Changes), Yekaterinburg: UrO, Ross. Akad. Nauk, 2009.
12. Shiyatov, S.G., Vaganov, E.A., Kirdyanov, A.V., Kruglov, V.B., Mazepa, V.S., Naurzbaev, M.M., and Khantemirov, R.M., *Metody dendrokhronologii* (Methods of Dendrochronology), Krasnoyarsk: Krasn. Gos. Univ., 2000, part 1.
13. Yarmishko, V.T., *Sosna obyknovennaya i atmosfernoe zagryaznenie* (Scots Pine and Air Pollution), St. Petersburg: Nauchno-Issled. Inst. Khim., 1997.
14. *Elektronnyi uchebnik po statistike* (Electronic Manual on Statistics), Moscow: StatSoft, 2001. http://www.statsoft.ru/home/textbook/default.htm
15. Bakkal, I.J., The effect of fire and air pollution on the field layer in pine forests in the Kola Peninsula, in *Proc. Int. Workshop "Aerial Pollution in Kola Peninsula," St. Petersburg, April 14–16, 1992*, Apatity, 1993, pp. 299–307.
16. Boettger, T. and Friedrich, M., A new serial pooling method of shifted tree ring blocks to construct millennia long tree ring isotope chronologies with annual resolution, *Isot. Environ. Health Stud.*, 2009, vol. 45, no. 1, pp. 68–80.
17. Cook, E.R., A time series analysis approach to tree ring standardization, *PhD Dissertation*, Tucson, AZ: Arisona Univ. Press, 1985.
18. Cook, E.R., Briffa, K.R., Shiyatov, S.G., and Mazepa, V.S., Tree-ring standardization and growth-trend estimation, in *Methods of Dendrochronology. Application in the Environmental Sciences*, Cook, E.R. and Kairiukstis, L.A., Eds., Dordrecht, Netherlands: Kluwer, 1990, pp. 104–123.
19. Eronen, M., Zetterberg, P., Briffa, K.R., Lindholm, M., Merilainen, J., and Timonen, M., The supra-long Scots pine tree-ring record for Finnish Lapland. Pt 1. Chronology construction and initial influences, *Holocene*, 2002, vol. 12, no. 6, pp. 673–680.
20. Fedorkov, A., Effect of heavy metal pollution of forest soil on radial growth of Scots pine, *For. Pathol.*, 2007, vol. 37, no. 2, pp. 136–142.
21. Fritts, H.C., *Tree-Rings and Climate*, London: Academic, 1976.
22. Kononov, Yu. M., Friedrich, M., and Boettger, T., Regional summer temperature reconstruction in the Khibiny Low Mountains (Kola Peninsula, NW Russia) by means of tree-ring width during the last four centuries, *Arct. Alp. Res.*, 2009, vol. 41, no. 4, pp. 460–468.
23. Savva, Y. and Berninger, F., Sulphur deposition causes a large-scale growth decline in boreal forests in Eurasia, *Global Biogeochem. Cycles*, 2010, vol. 24, p. GB3002. doi: 10.1029/2009GB003749
24. *The Laboratory of Tree-Ring Research*, Software & Data, 2005. http://www.ltrr.arizona.edu/software.html
25. Valkama, J. and Kozlov, M.V., Impact of climatic factors on the developmental stability of mountain birch growing in a contaminated area, *J. Appl. Ecol.,* 2001, vol. 38, no. 3, pp. 665–673.

Translated by S. Semenova