ISSN 0012-4966, Doklady Biological Sciences, 2024, Vol. 518, pp. 205–217. © Pleiades Publishing, Ltd., 2024.
ISSN 0012-4966, Doklady Biological Sciences, 2024. © Pleiades Publishing, Ltd., 2024.
Russian Text © The Author(s), 2023, published in Rastitel'nye Resursy, 2023, Vol. 59, No. 1, pp. 76–92.

Dependence of *Pinus sylvestris* (Pinaceae) Radial Growth on Meteorological Conditions and Anthropogenic Air Pollution: Data from Northwestern Part of Murmansk Oblast

I. V. Romashkin[a,*], N. V. Genikova[a], A. M. Kryshen[a], S. A. Moshnikov[a], and N. V. Polikarpova[b]

Received May 20, 2024; revised May 29, 2024; accepted June 6, 2024

Abstract—The influence of meteorological factors and anthropogenic air pollution on the radial growth of the Scots pine *Pinus sylvestris* L. was studied as dependent on the distance from the Pechenganickel mining and metallurgical plant (Nikel, Murmansk region). Three (control, buffer, and impact) zones of the pollution gradient were identified based on the contents of main polluting elements (S, Ni, and Cu) in the forest litter. A significant weakening of pine stands was observed in the impact zone and attributed to the combined effect of long-term anthropogenic pollution of the 1970s and unfavorable weather events of the mid-1980s. As the emission decreased from 1988 to 2018, the radial increment of *P. sylvestris* was observed to increase significantly (by up to 44%) in the impact zone and to remain much the same in the control and buffer zones. More recently, the radial increment of trees in the impact zone reached and even exceeded the values observed in the control zone, although the trees examined were relatively old. The finding demonstrated again the high adaptive capacity of *P. sylvestris*.

Keywords: *Pinus sylvestris*, Scots pine, radial increment, anthropogenic pollution, climate, monitoring

DOI: 10.1134/S0012496624701151

INTRODUCTION

Extraction, metallurgical, and wood processing facilities negatively affect their adjacent areas, inevitably leading to a lower productivity, instability, and gradual degradation of forest ecosystems [1, 2]. The greatest anthropogenic impact is associated with copper-nickel plants, which pollute the atmosphere by releasing substantial amounts of sulfur dioxide (SO_2) and heavy metals, in particular, copper (Cu) and nickel (Ni) [3]. Although diverse pollutant migration pathways are observed in terrestrial ecosystems, plant components (producers) are involved in most cases [4]. A decrease in the stability of forest communities exposed to anthropogenic pollution is accompanied by changes in the forest stand structure and an increase in the proportion of weakened and dead trees [5]. The intensity of water transport may decrease in trees with the decreasing distance from an emission source, damaging the assimilation system and consequently reducing both vertical and radial growth rates [2, 6, 7].

[a] *Forest Research Institute, Karelian Research Center, Russian Academy of Sciences, Petrozavodks, Russia*
[b] *Pasvik State Nature Reserve, Nikel, Russia*
**e-mail: romashkin@krc.karelia.ru*

The radial increment (RI) is one of the most informative parameters which capable of reflecting the effects that various factors have exerted on the growth of a tree throughout its life [8–10]. Patterns of RI variation are determined by both the tree species identity and the combined effect of ecological and climatic conditions [11]. A significant decrease in RI with the increasing pollution has been observed in most studies [12–14] and is accompanied by an increase in the amplitude of RI fluctuations and the disruption of its cyclicity. Such observations have been made both locally and in total Eurasia [13]. It should be noted that RI strongly depends on climatic fluctuations, and this fact is important to consider when studying the effects of anthropogenic pollution on the tree growth [15–17].

Relatively short periods of time (e.g., a few decades) have been considered in most studies of the effect of anthropogenic pollution on forest ecosystems [13]. In 2018, a network of permanent sample plots (SPs) was established in the Pasvik Nature Reserve and adjacent areas (Murmansk Oblast) by the Institute of Forest Research in order to monitor the dynamics of north taiga forests in conditions of climate changes and anthropogenic air pollution. The choice of a object for the long-term monitoring was determined by the temporal variations in works at the Pechenganikel' mining and metallurgical plant because several periods differing in anthropogenic loading could be

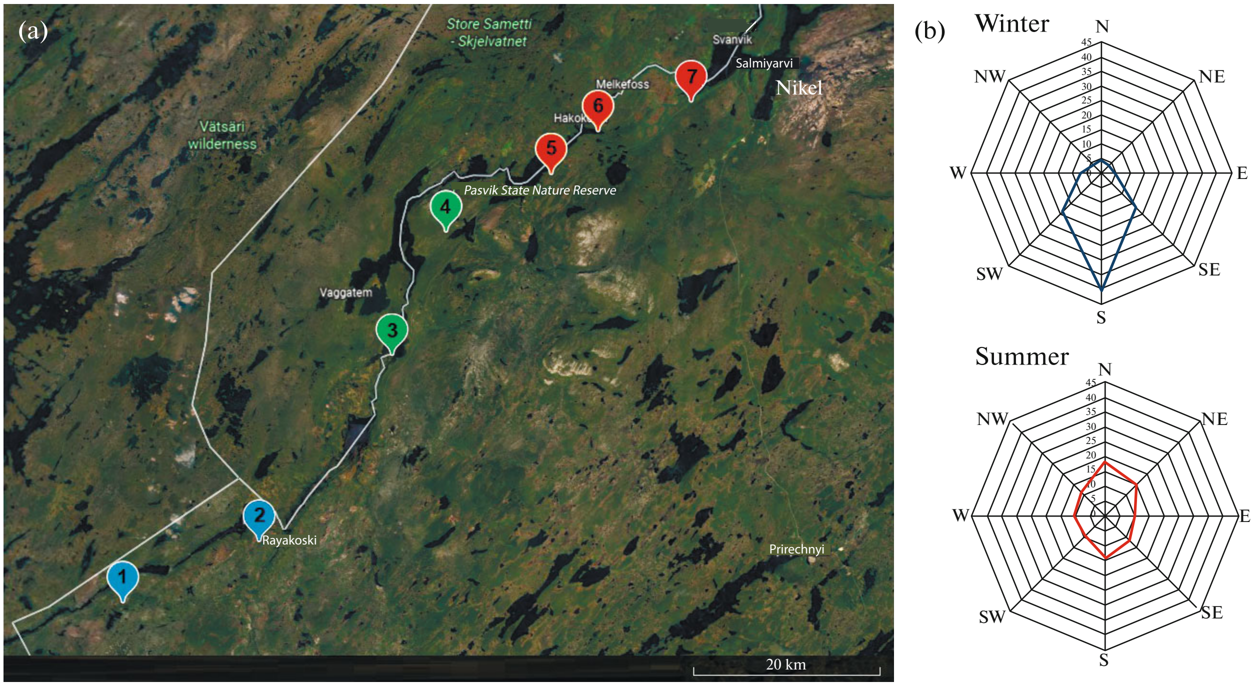

Fig. 1. (a) Locations of the permanent SPs at different distances from the source of anthropogenic air pollution (Pechenganikel' plant, Nikel). Pollution zones are color coded: blue, control zone (SPs 1 and 2); green, buffer zone (SPs 3 and 4); red, impact zone (SPs 5–7). (b) Summer and winter wind roses of the town of Nickel.

isolated. Intense industrial development of the region started in 1930s, and the plant started operating in 1937. Copper and nickel production peaked in the 1970s. More than 1 million tons of Norilsk ore material was delivered to the Pechenganikel' and Severonikel' plants by that time, and the sulfur (S) content in the ore (approximately 30%) was substantially higher than in ore from Kola mines (up to 5%). The total SO_2 release consequently reached 411 thousand tons in 1977. When the first (1981) and second (1987) sulfuric acid production lines were launched, SO_2 emission decreased by 10.9 and 27.2%, respectively. Ore from Norilsk mines was gradually rejected from 1992 and 2002, leading to a stable decrease in SO_2 emission. More recent optimization measures, including reengineering of converter gas removal systems and improvement of sulfuric acid production, reduced the SO_2 emission to 50–56 thousand tons/year (2010); Ni emission, to 250 tons/year; and Cu emission, to 130 tons/year (2015) [3, 18]. The Pechenganikel' plant stopped operating in 2021.

The objective of this work was to study the response of Scots pine *Pinus sylvestris* L. trees to the changes in atmospheric emissions from the copper and nickel production plant Pechenganikel' (town of Nikel). We (1) studied the RI dynamics in *P. sylvestris* trees growing at various distances from the pollution source; (2) determined the effect of climatic (meteorological) parameters, such as average monthly temperature and average monthly precipitation, on the RI dynamics in *P. sylvestris*; and (3) determined the effect of the emission of main pollutants from copper and nickel industry (SO_2, Ni, and Cu) on the RI dynamics. We assumed that RI decreases gradually with the increasing pollution and that RI fluctuations are due to both changes in pollutant emission and climatic (weather) extremums. A decrease in anthropogenic pollution, both in temporal and spatial aspects, was expected to benefit the *P. sylvestris* growth.

MATERIALS AND METHODS

Pinus sylvestris stands were examined in the Pasvik State Nature Reserve (Pechenga District, Murmansk Oblast) and the adjacent area. Seven permanent SPs were established at different distances of the Pechenganikel' plant (town of Nikel) (Fig. 1). The minimal distance between a SP and the plant as a source of anthropogenic pollution was 11 km (SP 7); the maximal distance was 82 km (SP 1). Characteristics and geographic coordinates of the SPs are summarized in Table 1.

Based on the S, Ni, and Cu contents in the forest litter (horizon O), the study area was divided into zones differing in anthropogenic pollution level. The S content in the forest litter changed only slightly with the decreasing distance from the pollution source, while the heavy metal contents increased significantly. Three zones were therefore determined. A control zone (SPs 1 and 2) had the Cu and Ni average contents

Table 1. Characteristics of the *P. sylvestris* forest stands examined in this work

Sample plot	Forest type	Distance to source of pollution, km	Tree species composition	Mean		Site index	Health class	Stand density, abs./rel.	Number of trees per ha	Growing stock, m^3/ha	Coordinates, UTM (WGS84)
				$D_{1.3}$, cm	H, m						
1	Pinetum vacciniosum	81	9.7P 0.3B	18.6	12.5	V–Va	1.91	20.1/0.67	790	132	35W 0567234 7648097 68,93558N 28,67637E
2	Pinetum vacciniosum	68	10P + B	18.4	12.1	V–Va	1.18	19.9/0.68	870	117	35W 0579541 7655173 68,99571N 28,98872E
3	Pinetum vacciniosum	48	10P + B	19.7	12.3	Va	2.05	16.4/0.56	550	81	35W 0590192 7672418 69,14695N 29,27073E
4	Pinetum empetrosum	37	10P + B	20.8	11.3	V–Va	2.60	15.5/0.55	470	90	35W 0594306 7686138 69,26849N 29,38765E
5	Pinetum empetroso-vacciniosum	26	9.8P 0.2B	17.7	9.6	Va	2.27	12.5/0.47	600	65	35W 0603805 7692340 69,32056T 29,63459E
6	Pinetum empetroso-vacciniosum	21	9.8P 0.2B	20.3	11.4	V–Va	2.77	13.4/0.47	520	81	35W 0607724 7697060 69,36130N 29,73928E
7	Pinetum empetroso-vacciniosum	11	8.5P 1.5B	13.8	9.4	Va	2.63	19.2/0.71	1070	100	35W 0616250 7700754 69,39083N 29,96027E

Designations: P, *P. sylvestris;* B, *Betula pubescens*; $D_{1.3}$, stem diameter at 1.3-m height; H, height.The most typical parts of forest stands were used to establish permanent SPs. Mensurational studies were carried out by a common method. All (both living and standing dead) trees were counted, and their diameters were measured accurate to 0.1 cm. The height was measured in 20–25 trees per SP with a Suunto clinometer. A Pressler increment borer was to collect core samples from 5–8 trees per SP; samples were taken from the stem base and used to estimate the tree ages. Living ground vegetation and the soil morphological structure were described additionally. The tree type was determined based on the findings above.

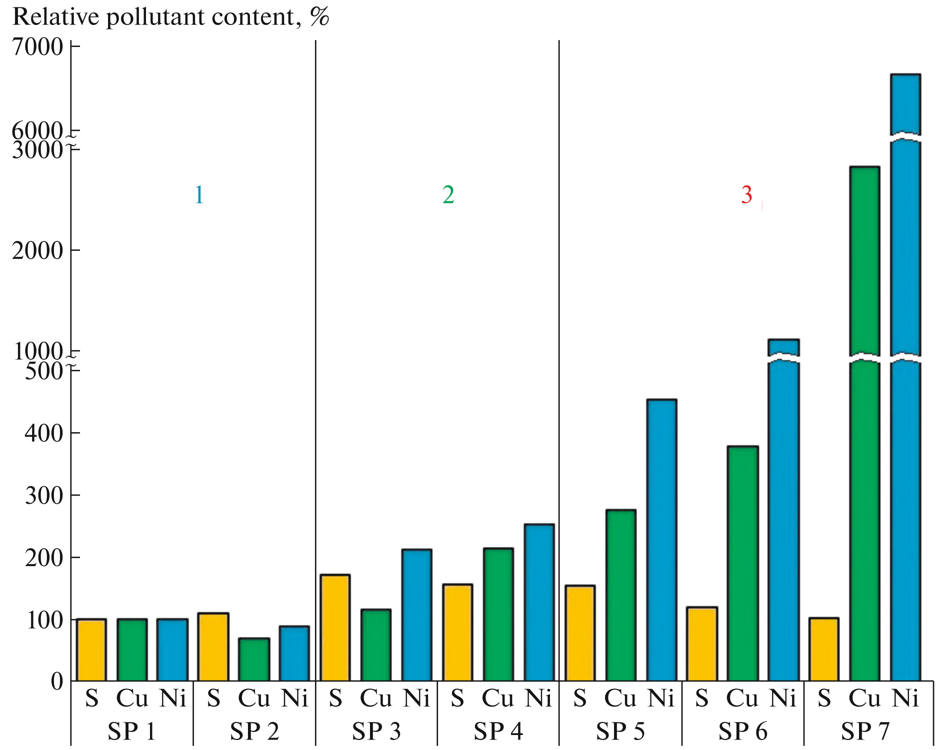

Fig. 2. Contents of the pollutants (S, Cu, and Ni) in the forest litter (horizon O) at SPs examined. Pollution zones: 1, control zone (SPs 1 and 2); 2, buffer zone (SPs 3 and 4); 3, impact zone (SPs 5–7). X axis, pollutants; Y axis, pollutant content relative to the control (SP 1) (%).

of 19.9 and 12.0 mg/kg, respectively. A buffer zone (SPs 3 and 4) had the Cu and Ni average contents of 31.8 and 33.2 mg/kg, respectively. In an impact zone (SPs 5–7), the Cu and Ni contents reached 728.6 and 879.0 mg/kg, respectively, and exceeded the control values by factors of 28.2 and 65.2, respectively (Fig. 2).

Permanent SPs were laid in the most typical places of forest areas. Forest inventory was carried out according to a generally accepted method. A complete count of all trees (living and dead) was performed, the diameter was determined with an accuracy of 0.1 cm. The height of 20–25 trees on the SP was measured using the Suunto altimeter. Using the Pressler age drill, the cores were taken at the trunk base of 5–8 trees to determine the age. Additionally, a description of the living ground cover and morphological structure of the soils was conducted. Based on these characteristics, the forest type was determined.

The stand condition was assessed in a forest pathology study using a scale from Rules of Sanitary Safety in Forests [19]. The living tree condition was inferred from a set of main external characters, including needle color and age, crown scaffold thinning, and the proportion of dead and dying branches. The effects of pathological forest factors (fungal diseases and pest insects) were evaluated. The core samples were checked for stem rot. The above tree condition parameters were used to calculate the mean health score of the stand (Table 1).

Soil samples were examined using equipment of the Collective Use Center “Analytical Laboratory” of Forest Research Institute (Karelian Research Center). The S content was measured by the Rin’kis method (SF-200). The Ni and Cu contents were assessed by atomic absorption spectrometry, using AA-6800 and AA-7000 Shimadzu instruments. To measure the metal contents, sample decomposition was carried out using a Speedwave Four microwave digestion system (Berghof, Germany).

To study the RI variation in *P. sylvestris*, 10–15 trees of a broad age range (150–250 years) were selected to represent all of the SPs. Core samples were taken from the side facing southward at a 1.3-m height. The samples were glued onto a wooden base, their surfaces were ground and smoothed. Each sample was scanned at a resolution of 1600 dpi. The mean annual ring width was determined using Cdendro/CooRecorder 9.3 software with due regard to all bends [20]. A graphical analysis of the sample was carried out by a crossdating method [21]. A RI plot based on mean values (n = 20–45) was constructed for each of the groups differing in distance from the industrial plant. To assess the tree response to changes in environmental conditions, the RI index was calculated as a ratio of actual RIs to theoretical RIs, which were calculated from parameters of the age trend function [22]. All series of RI, RI index, and climatic variable values were averaged using a 5-year moving average to minimize the high-frequency component [23].

Annual layers were marked in the core samples with respect to five main periods of industrial plant activity with different amounts of pollutant emission: (1) from 1937 to 1970, an initial period; (2) from 1971 to 1980, a period of using ore with a high S content from Norilsk mines; (3) from 1981 to 1987, a period when SO_2 emission decreased due to reengineering activities; (4) from 1992 to 2002, a period when ore from Norilsk mines was rejected; and (5) from 2001 to 2018, a modern period of work optimization. Data on the pollutant amounts emitted from the Pechenganikel' plant from 1977 to 2015 were obtained from the available literature [3, 18].

Climatic data, including monthly average temperatures of the surface air layer and monthly average precipitations (Yaniskoski, weather station 22101), were retrieved from a specialized dataset of climatic data of the All-Russia Research Institute of Hydrometeorological Information–World Data Center [24]. A hydrological year was defined as a period lasting from October of a previous calendar year to September of the current year; a winter season, as a period from October of a previous calendar year to April of the current year; and a vegetation season, as a period from May to September of the same year. Selyaninov's hydrothermal coefficient (HTC) was calculated from the following equation [25]:

$$\mathrm{HTC} = (\Sigma P/\Sigma_{t10}) \times 10 \tag{1}$$

where ΣP is the sum of precipitations over a period with temperatures higher than 10°C and $\Sigma\ t_{10}$ is the sum of temperatures exceeding 10°C over the same period.

The effective temperature sum (ETS) of temperatures that are higher than 5°C and are necessary for triggering the growth processes in *P. sylvestris* [26] was calculated as

$$\Sigma i = 1 \text{ to } 12(\max(0; \mathrm{N}ix(T_{\mathrm{avg}} - 5))), \tag{2}$$

where Σi is the ETS of temperatures higher than 5°C (degree–day), 1–12 are months of the year, Ni is the number of days in a month, and T_{avg} is the monthly average air temperature (°C).

Statistical analyses were carried out using the R software package [27] with generalized linear models (GLMs) and the Duncan multiple range test. Data distributions were checked for normality by the Shapiro-Wilk W-test and subject to the Box–Cox transformation when necessary.

RESULTS AND DISCUSSION

RI Dynamics in P. sylvestris as Dependent on Distance from Pollution Source

Differences in *P. sylvestris* RI dynamics were observed along the pollution gradient in an analysis of averaged chronologies (Fig. 3). In the control zone, a stable descending trend was observed for RI from 1939 to 1970 (linear regression coefficient $A = -0.010$) and a cyclic character was preserved. A substantial decrease in RI was observed in the next years ($A = -0.001$). Lower RI extremums corresponded to years 1929, 1946, 1968, 1987, 2000, and 2013; upper extremums, to years 1941, 1960, 1973, 1993, and 2003. The mean RI in the control zone was 0.76 mm/year (SE = ±0.02) as averaged over the total observation period (from 1918 to 2018).

In the buffer zone, the RI dynamics was much the same as in the control zone, with the exception of the past decade of the period under study. Synchrony of RI changes was distorted in the past decade. The general trend of RI changes was descending in the buffer zone, like in the control zone. The slope observed in the period from 1939 to 1970 was slightly lower than in the control zone ($A = -0.006$), while the slope observed from 1971 to 2018 was similar to that in the control zone. The mean RI was 0.46 mm/year (SE = ±0.01), lower than in the control zone.

In the impact zone, the *P. sylvestris* RI dynamics observed before the most intense anthropogenic loading of the 1970s was generally similar to the dynamics in the control zone. The mean RI in the impact zone in the period from 1918 to 1970 was 1.01 mm/year (SE = ±0.04), which was 16% higher than in the control zone in the same period. Chernenkova [29] have reported a similar regularity for *P. sylvestris* trees younger than 50 years of age from regions near the Pechenganikel' plant. The finding suggests not only suppression, but also stimulation of growth processes [28, 29]. Our data at least do not contradict this assumption.

Starting from 1970, RI of *P. sylvestris* trees from the impact zone decreased more intensely than in the control zone ($A = -0.012$) and showed its lowest value (0.23 mm) in 1987. A decrease in RI from 1985 to 1987 was detected in all of the trees examined, regardless of the distance from the pollution source. The mean RI observed in the control zone in this period was 0.54 mm/year (SE = ±0.02), 29% lower than the RI averaged over the total observation period. In the buffer and impact zones, RIs were 0.42 mm/year (SE = ±0.01) and 0.33 mm/year (SE = ±0.03), respectively; i.e., the values were 46 and 58% lower, respectively.

In the following period, the RI dynamics substantially differed between the zones. RI stabilized in trees of the control and buffer zones. A stable ascending trend was observed for RI of *P. sylvestris* trees in the impact zone. For example, the mean RI in the period from 1988 to 2018 was 44% higher than in the period

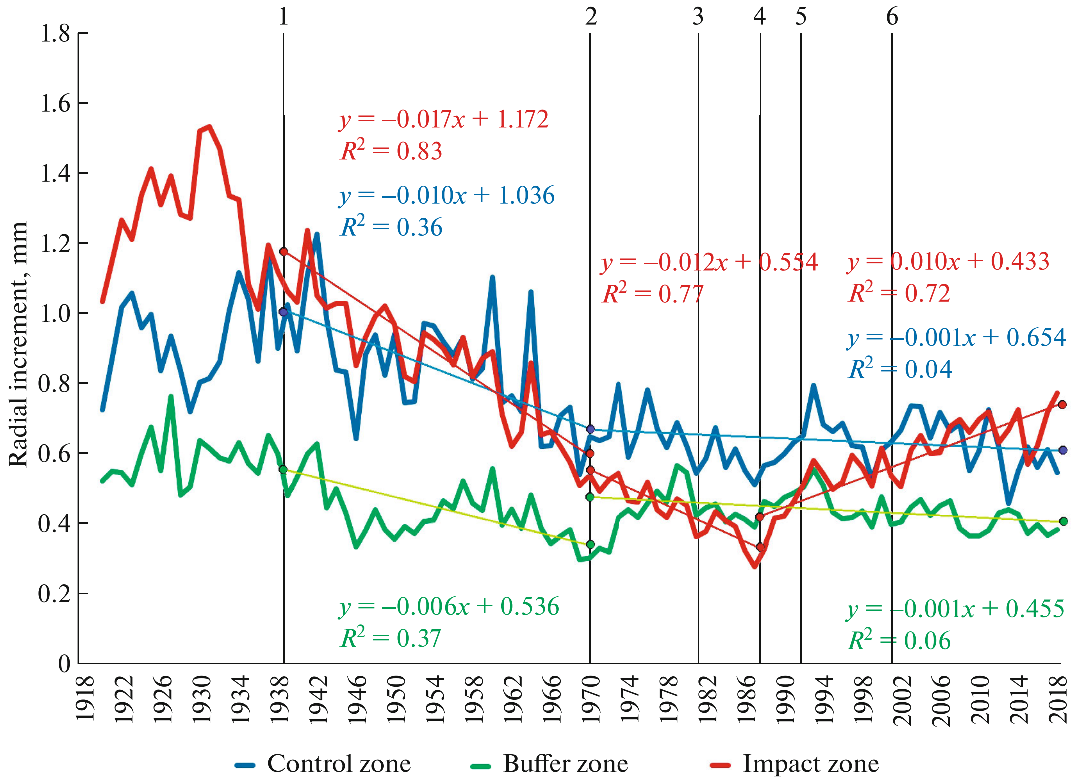

Fig. 3. Dynamics of *P. sylvestris* RI from 1918 to 2018 as dependent on the distance from the pollution source. Main periods of Pechenganikel' operation: 1, 1937, start of operation; 2, 1970, start of Norilsk high-sulfur ore processing; 3–4, from 1981 to 1987, reduction of SO_2 emissions due to the modernizations; 5, from 1992 to 2002, cessation of Norilsk ore processing; 6, from 2001 to 2018, production optimizations. X axis, year; Y axis, RI, mm.

Fig. 4. The tree crown shape in the impact zone indicates an improvement in *P. sylvestris* growth.

from 1985 to 1987. Thus, although a greater decrease in RI was observed in 1987 in the impact zone compared with the control and buffer zones, where the anthropogenic load was lower, RI stably increased in the next years in the impact zone ($A = 0.010$). Moreover, RIs of trees of the impact zone were similar or even higher than in the control zone after 2007, although the mean age of the trees was relatively old.

An improved growth of some *P. sylvestris* trees in the impact zone was detectable visually. The crown became conical in shape in recent years (Fig. 4), while a conical crown is usually characteristic of intensely growing trees. The finding confirmed the earlier observation that *P. sylvestris* preserves its growth potential at an age of 180 years and older and fulfils it when the growth conditions improve [22]. It is of particular interest that only trees growing in a highly polluted zone displayed this capability. We cannot predict how long the period of intense *P. sylvestris* growth will continue after anthropogenic air pollution decreased and then ceased in 2021. The issue was among the problems to be solved by establishing the long-term monitoring network.

Because *P. sylvestris* RI was observed to change along the pollution gradient, being lower in the buffer zone than in the impact zone, it seems difficult to select sample plots (first of all, control ones) for dendrochronological studies. A certain age difference between the trees examined in different zones seems to be more significant to the observed discrepancy. The mean tree ages were 167 years (SE = ±10) in the control zone, 205 years (SE = ±11) in the buffer zone, and 165 years (SE = ±7) in the impact zone. The difference explains while RI observed in the control zone was lower in the early study period and showed a smoother trend over time. The studied sample plots additionally differ in history of pyrogenic damage, which was caused mostly by ground fires varying in intensity and occurring 110 (SPs 3, 5, and 6) to 200 (SPs 2 and 7) years ago. Fires certainly affected the age structure and other characteristics of studied tree stands.

As the anthropogenic load is increasing, it becomes more difficult to separate the changes that occur naturally in *P. sylvestris* RI from the changes that are due to intense human activities [16]. Among apparent anthropogenic effects, traces of selective cuttings, which varied in intensity from 10 to 20% and were performed approximately 30–50 years ago, were detected in almost all SPs (with the exception of SP 1). In addition, three hydroelectric power plants were constructed in the 1950s in the region of the Rayakoski village (the Paz River) (SP 2) [3]. Their construction was likely to substantially affect the local conditions and, therefore, RIs of trees in the region [18]. Moreover, an anthropogenic effect cannot be totally excluded in the case of forest stands of the control zone, although they were sufficiently far (>70 km) away from the pollution source and showed no sign of weakening.

Effects of Meteorological Parameters on P. sylvestris RI

Air temperature was found to greatly vary over the vegetation season in the study region. In the period from 1955 to 2019, monthly average air temperatures in the village of Yaniskoski (SP 1) were 4.3°C (0.9–10.6°C) in May, 10.2°C (5.9–14.3°C) in June, 13.7°C (9.2–18.8°C) in July, 11.3°C (8.6–13.6°C) in August, and 6.4°C (2.8–9.1°C) in September. A certain periodicity of colder and warmer years was observed. Monthly average temperatures of the vegetation period were lower than the respective long-term average values in 1965, 1977, 1981, 1987, and 2008. The May monthly temperature decreased to the greatest extent in those years, probably delaying the start of the vegetation period and reducing its duration. Abnormally low May monthly temperatures (at least 50% lower than the long-term average) were observed rather often, in 1955, 1958, 1965, 1969, 1985, 1996, and 1999 (Table 2). Abnormally warm May weather was detected in 1960, 1963, 1984, 1989, 1992, 2010, 2013, 2016, and 2018 (Table 2). This rotation of warmer and colder years generally corresponds to the 11-year Schwabe cycles of solar activity [30], as is especially characteristic of northern latitudes [31].

The annual yearly precipitation was 515 mm (340–674 mm) in the study area in the period from 1970 to 2019. Within a year, the greatest precipitation level was observed in summer. The seasonal average total precipitation was estimated at 84 mm (44–136 mm) in winter, 96 mm (35–169 mm) in spring, 202 mm (98–354 mm) in summer, and 133 mm (67–210 mm) in autumn (Table 3). Four drought periods are possible to recognize in the study period: summer 1980, autumn 1984–spring 1987, summer 1991, and summer 2013. The longest drought period was observed from 1984 to 1987 and moreover the air temperature during the vegetation season in those years was lower than its long-term average.

In 1985, air monthly temperatures were relatively low in May, June, and September and similar to the long-term average in July and August, while the annual precipitation was only 340 mm, which is 34% lower than the respective average over the total observation period. Unfavorable weather conditions culminated in 1987, when general cooling was accompanied by a long-term drought. Although the above weather events certainly exerted a substantial effect on *P. sylvestris* growth, correlation analyses did not detect significant associations between the meteorological parameters and absolute RI values or RI index (Table 4).

An analysis of RI correlations with meteorological parameters did not yield unambiguous results; most correlations were statistically non-significant. Moderate correlations were observed for RI with February and May monthly temperatures, HTC, ETS, total precipitation of October of the previous year, total precipitation of July of the current year, and total precipitation over the vegetation season (Table 5). RI index showed the greatest values of the coefficient of correlation R when tested for association with meteorological parameters. The coefficients of correlation established for RI indexes observed in the control and impact zones were, respectively, 0.37 and 0.35 with May monthly temperature and 0.46 and 0.40 with June precipitation. In total, the findings confirmed the general regularities of the tree response to changes in weather conditions. That is, RI depends more on the sum of positive temperatures in the first half of the vegetation period and on the total precipitation in the second half of the vegetation period [32, 33]. No regular change along the pollution gradient was observed for the associations of RI or RI index with the above meteorological parameters.

In spite of the relatively weak correlations between the parameters under study, weather conditions still greatly affect RI over the vegetation season. Vaganov et al. [34] have shown that positive temperature-dependent determination of growth increments in trees of the subarctic zone varies from 50 to 80% and

Table 2. Difference (%) of monthly average temperature over the vegetation season and long-term averages for the period from 1955 to 2018 (Yaniskoski, SP 1)

Year	May	June	July	August	September	Year	May	June	July	August	September
2018	**83.7**	–3.8	35.3	11.1	3.3	1986	2.3	27.6	–7.1	–16.4	4.9
2017	**–44.2**	–17.6	5.3	–2.2	29.9	**1985**	**–58.1**	–1.9	3.9	5.8	–21.8
2016	**95.3**	6.0	13.4	0.4	**42.4**	**1984**	**74.4**	7.9	–15.1	–9.3	22.1
2015	39.5	–3.8	–21.7	13.8	11.1	1983	14.0	–0.9	1.7	–12.9	–4.5
2014	–4.7	–4.8	15.6	16.4	31.5	1982	–14.0	–42.1	3.1	–8.4	–10.8
2013	**97.7**	**40.3**	6.1	20.0	4.9	**1981**	**–20.9**	**–30.3**	**–2.0**	**–10.2**	**–1.4**
2012	30.2	–5.8	–10.0	–6.7	31.5	1980	–30.2	25.6	–9.3	–6.7	11.1
2011	25.6	15.8	6.8	–3.1	15.8	1979	0.0	7.9	3.1	4.0	–13.9
2010	**48.8**	–9.7	5.3	–8.4	26.8	1978	4.7	–1.9	–16.6	–13.8	–21.8
2009	32.6	–9.7	–10.0	11.1	–15.5	**1977**	**–30.2**	**–15.6**	**–3.4**	**–6.7**	**–39.0**
2008	–20.9	–7.8	–7.8	–17.3	–10.8	1976	37.2	–21.5	–2.7	0.4	15.8
2007	0.0	0.1	–8.6	12.9	–1.4	1975	18.6	–21.5	–16.6	–16.4	39.3
2006	34.9	17.8	–5.6	14.7	1.7	1974	–34.9	17.8	14.9	5.8	**–51.5**
2005	–16.3	9.9	6.8	13.8	11.1	1973	–2.3	19.7	27.3	–7.6	–9.2
2004	14.0	–5.8	25.1	4.9	–3.0	1972	–25.6	38.4	26.6	17.3	–18.6
2003	34.9	–12.7	22.2	0.4	–13.9	1971	–30.2	–10.7	–8.6	0.4	–3.0
2002	27.9	9.9	7.5	2.2	28.3	1970	–7.0	30.5	14.9	15.6	n/a
2001	–23.3	18.7	3.9	–4.0	11.1	**1969**	**–58.1**	**–14.6**	n/a	n/a	**–43.7**
2000	7.0	–4.8	2.4	1.3	28.3	**1968**	**–79.1**	**–5.8**	**–32.7**	**–10.2**	26.8
1999	**–65.1**	28.8	1.7	–16.4	–15.5	1967	0.0	–0.9	–2.0	17.3	–43.7
1998	–25.6	–26.4	4.6	–11.1	29.9	1966	–34.9	12.9	3.1	–12.9	3.3
1997	–23.3	–1.9	6.8	20.9	–10.8	**1965**	**–76.7**	**–5.8**	**–23.9**	**–12.0**	**–21.8**
1996	**–72.1**	–16.6	–9.3	19.1	–9.2	1964	2.3	–3.8	6.1	–4.9	37.7
1995	–18.6	14.8	–15.1	–4.0	–17.1	**1963**	**146.5**	–21.5	–12.9	1.3	–9.2
1994	–23.3	–7.8	3.1	7.6	**–56.2**	1962	–25.6	–14.6	–21.7	–18.2	3.3
1993	–4.7	–36.2	1.0	–0.4	37.7	1961	–37.2	25.6	8.3	4.0	9.5
1992	**53.5**	17.8	–15.9	–15.6	n/a	**1960**	**86.0**	6.0	37.5	10.2	–24.9
1991	–18.6	3.0	n/a	n/a	–15.5	1959	37.2	1.1	–2.7	12.0	–4.5
1990	–16.3	–3.8	–2.7	5.8	6.4	**1958**	**–72.1**	–1.9	–13.7	9.3	–9.2
1989	**55.8**	24.6	–1.2	6.7	11.1	1957	–34.9	–15.6	19.2	7.6	–32.7
1988	–4.7	12.9	13.4	–0.4	–4.5	1956	23.3	19.7	–17.3	–20.0	1.7
1987	**–14.0**	**–11.7**	**–17.3**	**–23.6**	**–43.7**	**1955**	**–51.2**	**–31.3**	**–8.6**	12.0	**40.8**

The most significant extremes are in bold.

increases northward. The most favorable temperature of conifer growth in the northern taiga subzone ranges from 13 to 20°C. Temperatures outside this range decrease RI [35]. It seems likely that a decrease in monthly average temperature of May reduces the vegetation season and thereby decreases the intensity of *P. sylvestris* growth in severe arctic conditions. The role of precipitation compared with the role of temperature regime decreases northward [35, 36]. Mulgauzen and Pankratova [18, 37] have studied *P. sylvestris* RI in similar conditions along a pollution gradient and observed significant associations of RI with both air temperature and precipitation. Somewhat stronger associations of RI with meteorological parameters have been established for the impact zone [14, 38]. At the same time, it cannot be excluded that anthropogenic pollution distorts the relationships between RI and climatic parameters [13, 39].

Our findings make it possible to assume that unfavorable weather events occurring in the vegetation period most strongly affect RI in *P. sylvestris*, the set including positive and negative temperature abnormalities and a lower precipitation. However, the cause-and-effect relationship between RI and meteo-

Table 3. Differences (%) between seasonal precipitation and the respective long-term averages for the period from 1970 to 2019 (Yaniskoski, SP 1)

Years	Autumn	Winter	Spring	Summer	Years	Autumn	Winter	Spring	Summer
2018–2019	–23.1	14.7	–12.3	–13.3	1993–1994	–13.7	29.9	–30.4	–12.8
2017–2018	–19.4	**41.8**	–3.1	**43.7**	1992–1993	–19.9	–9.4	19.0	4.1
2016–2017	3.1	**62.3**	–9.9	14.0	**1991–1992**	n/a	–14.8	–31.8	**75.8**
2015–2016	–33.2	14.0	–15.8	**75.4**	**1990–1991**	**–49.5**	11.0	2.7	**–49.7**
2014–2015	–32.6	–29.0	**60.8**	–7.4	1989–1990	–9.8	n/a	–23.3	–17.8
2013–2014	–1.4	–0.3	1.4	–12.5	1988–1989	4.0	–16.4	n/a	3.8
2012–2013	**57.6**	**–1.1**	**–15.3**	**–45.7**	**1987–1988**	**–41.0**	–14.7	–5.5	16.3
2011–2012	24.1	–34.9	5.0	2.4	1986–1987	–8.9	–19.4	–9.6	6.7
2010–2011	–9.0	–4.1	9.3	15.4	**1985–1986**	**46.7**	**–44.7**	–21.7	7.1
2009–2010	–18.0	–24.8	24.8	28.8	**1984–1985**	**–36.3**	**–26.6**	**–3.9**	**–49.5**
2008–2009	17.8	9.4	15.2	1.4	**1983–1984**	**42.1**	8.8	**57.2**	20.8
2007–2008	4.0	18.6	7.8	–23.7	1982–1983	0.2	–22.0	6.1	–33.8
2006–2007	–4.9	–25.1	30.6	21.2	1981–1982	–14.0	18.1	24.0	14.9
2005–2006	41.9	1.1	6.4	–13.4	1980–1981	13.5	–8.9	10.3	38.5
2004–2005	–1.4	21.4	**72.7**	–0.7	**1979–1980**	2.5	5.2	–10.4	**–51.4**
2003–2004	11.8	–38.6	14.4	13.3	1978–1979	0.0	29.3	–2.7	–34.3
2002–2003	–12.5	9.0	–10.0	4.8	1977–1978	–20.9	–8.5	–26.0	–8.7
2001–2002	–12.1	19.1	–23.1	–8.6	1976–1977	4.0	–10.1	37.3	22.3
2000–2001	–32.8	**58.0**	0.5	26.6	**1975–1976**	2.7	38.5	**–57.9**	–11.7
1999–2000	31.1	**–47.6**	**76.3**	–15.9	1974–1975	–13.8	35.5	39.8	3.3
1998–1999	n/a	n/a	–16.6	40.8	**1973–1974**	22.1	13.1	**–63.1**	22.8
1997–1998	–7.9	14.8	n/a	n/a	1972–1973	12.8	–34.9	–22.0	–13.1
1996–1997	1.8	**–44.5**	**–4.4**	**–37.3**	1971–1972	42.1	2.3	11.1	–31.0
1995–1996	**52.1**	–14.5	–10.0	–20.0	1970–1971	6.5	n/a	–38.1	–18.3
1994–1995	–15.2	18.6	–13.0	28.7	**1969–1970**	n/a	n/a	**–52.9**	–21.9

Note: The most significant extremes are given in bold

rological parameters may be distorted by anthropogenic pollution. We did not observe any significant change in RI response to weather conditions along the pollution gradient, but still cannot exclude that long-term exposure to anthropogenic pollutants increases the tree sensitivity to unfavorable weather events. In our study, the greatest decrease in RI was observed in *P. sylvestris* trees of the impact zone in the period of long-term drought and general cooling from 1985 to 1987. Thus, a combined effect of unfavorable weather events is probably one of the main factors responsible for a substantial decrease in RI in the impact zone, where trees are already weaker because of their long-term exposure to anthropogenic pollution.

Effect of Emission Regimen of Pechenganikel' Plant on RI dynamics in P. sylvestris

A comparison of the RI dynamics in *P. sylvestris* with the chronology of Pechenganikel' plant operation makes it possible to assume that a RI decrease observed from 1937 to 1970 was associated more with natural age-related factors and only partly with a gradual increase in anthropogenic load. Pollutant emission was maximal in the 1970s. However, the RI plot (Fig. 3) demonstrates that RI continued decreasing at least over the next decade. The decrease was explained in particular by unfavorable weather events of the mid-1980s. A certain lag is therefore possible to assume for the effect of anthropogenic pollution on trees. A lag is detectable in both negative effect on trees and their positive response to a decrease in emission. Our findings support the idea that *P. sylvestris* exposed to anthropogenic pollution for a long time is more sensitive to climatic extremes than in the control zone because the exposure weakens both individual trees and the total stand.

The emissions of the pollutants SO_2, Cu, and Ni gradually decreased in the past decades of plant operation [3, 18]. Correlation analyses showed that *P. sylvestris* RI and RI index in the impact zone were significantly associated with pollutant emissions. The

Table 4. Correlation coefficients of absolute RI (numerator) and RI index (denominator) of *P. sylvestris* with air temperature (T_{mean}) and precipitation (P_{mean})

Parameters	Pollution gradient		
	control zone	buffer zone	impact zone
T_{mean} (February)	0.16/**0.33**	**0.30**/0.14	0.03/0.27
T_{mean} (May)	0.19/**0.37**	0.21/0.22	0.24/**0.35**
HTC	0.01/0.18	–0.16/–0.18	0.26/**0.33**
ETS	0.27/0.11	–0.15/–0.08	0.10/**–0.31**
P_{mean} (October)	–0.15/**–0.31**	0.04/–0.11	–0.02/–0.22
P_{mean} (July)	0.29/**0.46**	0.04/0.12	0.17/**0.40**
P_{mean} (vegetation season)	0.28/**0.37**	0.04/0.02	0.26/0.27

T_{mean}, monthly average temperature; P_{mean}, monthly average precipitation; HTC, Selyaninov's hydrothermal coefficient; ETS, effective temperature sum. Statistically significant values are in bold.

Table 5. Correlation coefficients of absolute RI (numerator) and RI index (denominator) of *P. sylvestris* with emission levels of the main pollutants

Pollution gradient	SO_2, thousand tons/year	Cu, tons/year	Ni, tons/year
Control zone	–0.16/–0.11	–0.10/–0.18	–0.10/–0.23
Buffer zone	0.34/–0.01	0.38/–0.04	0.31/–0.01
Impact zone	**–0.87**/–0.23	**–0.71/–0.30**	**–0.61/–0.33**

Statistically significant values are in bold.

Table 6. Statistical parameters of the effect of pollutant emissions on *P. sylvestris* RI in the control, buffer, and impact zones (GLM, gamma distribution, inverse link function)

Pollutant	Equation parameters					Model parameters	
	coefficients	value	*SE*	*t*	*p*	R^2	*p*
SO_2	*Intercept*	1.5569	0.1050	14.87	< 0.001	0.17	< 0.001
	control zone	0.0001	0.0001	0.44	0.662		
	buffer zone	–0.0011	0.0007	–1.54	0.125		
	impact zone	**0.0034**	**0.0006**	**5.27**	**< 0.001**		
Cu	*Intercept*	1.5569	0.1841	8.46	<0.001	0.15	< 0.001
	control zone	0.0002	0.0009	0.25	0.806		
	buffer zone	–0.0019	0.0015	–1.23	0.219		
	impact zone	**0.0025**	**0.0007**	**3.58**	**< 0.001**		
Ni	*Intercept*	1.5750	0.0022	7.18	< 0.001	0.12	< 0.001
	control zone	0.0001	0.0006	0.12	0.906		
	buffer zone	–0.0011	0.0010	–1.05	< 0.294		
	impact zone	**0.0034**	**0.0009**	**3.58**	**< 0.001**		

SE, standard error; *t,* Student's *t*-test; *p*, significance level; R^2, coefficient of determination. Statistically significant values are in bold.

correlation coefficient *R* varied from –0.61 to –0.87, depending on the pollutant (Table 5). Similar data have been reported from other studies [3, 18, 40]. Mulgauzen and Pankratova [18] have not observed any difference in the coefficient of correlation between the above parameters in connection with the wind rose or the distance from a pollution source; i.e., trees of the control zone also responded to changes in pollutant emission from the plant. Our findings suggest the opposite; i.e., only *P. sylvestris* of the impact zone showed a significant effect of the pollutant emissions on RI (Table 5).

A data analyses with GLMs confirmed that significant effects of the SO_2, Cu, and Ni emissions on *P. syl-*

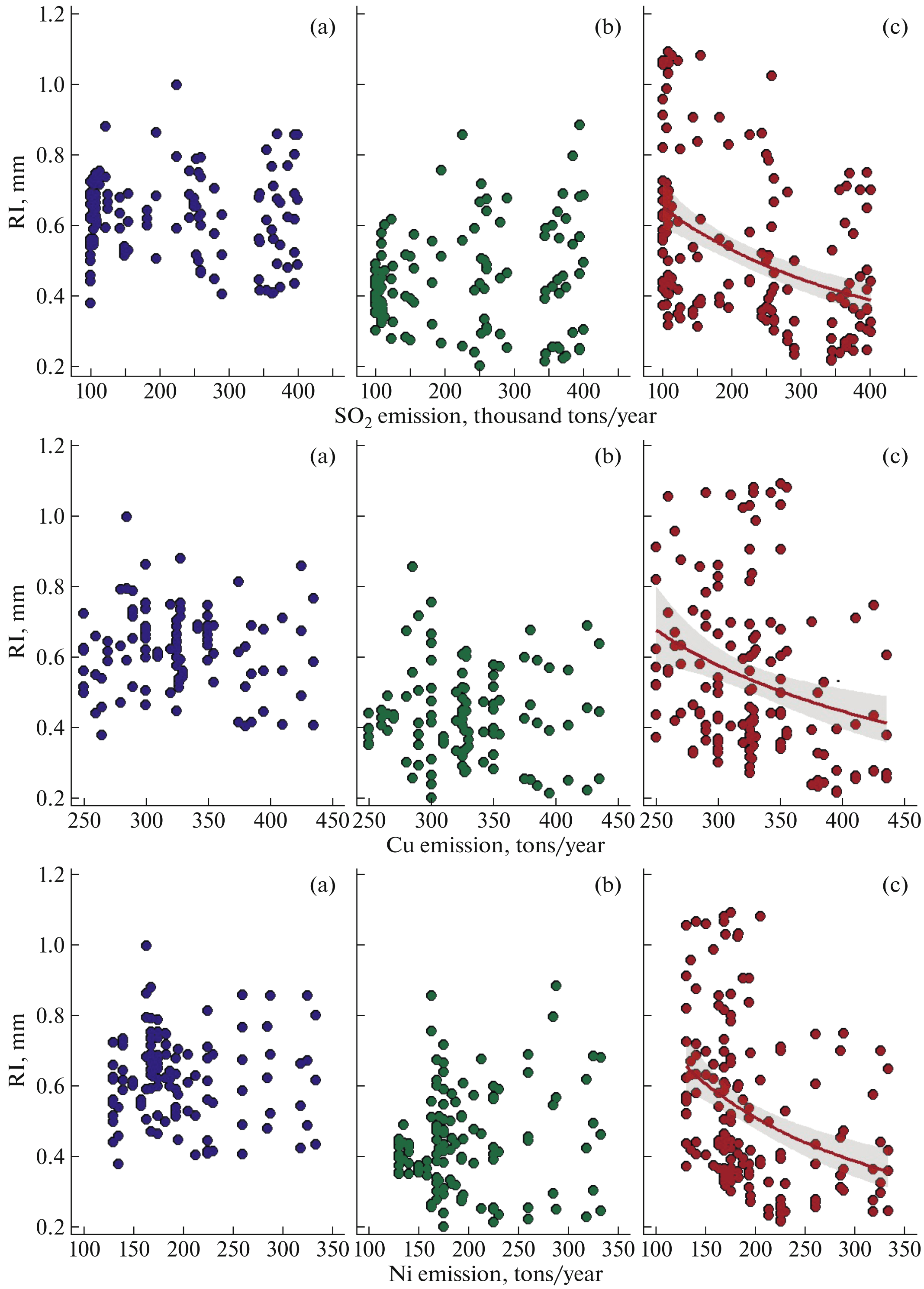

Fig. 5. Dependence of *P. sylvestris* RI on the emissions of the main pollutants SO_2, Cu, and Ni in the (a) control, (b) buffer, and (c) impact zones. X axis, emission (tons/year for Cu and Ni and thousand tons/year for SO_2); Y axis, RI (mm).

vestris trees were restricted to the impact zone (Table 6, Fig. 5). The increase in RI that was observed in the impact zone in the early 1990s was most likely associated with the fact that SO_2 and heavy metal emissions decreased as a result of a decrease in the Pechenganikel' plant production, a cumulative effect of modifications introduced in production and purification facilities, and a rejection of ore from Norilsk mines. Although the *P. sylvestris* trees examined in our work were relatively old, the above factors positively affected their growth and the condition of the studied pine stands in the impact zone.

CONCLUSIONS

Apart from a direct adverse effect of anthropogenic pollution, a set of unfavorable meteorological events was responsible for a dramatic decrease in RI observed in *P. sylvestris* stands near the Pechenganikel' plant in the mid-1980s. In addition, the set included a decrease in monthly average air temperature during the vegetation season and a low total annual precipitation in the period from 1985 to 1987. Starting from the 1990s, a significant increase in RI was observed in *P. sylvestris* trees of the impact zone. The increase reflected their positive response to a decrease in anthropogenic air pollution. In the next several years, RIs of trees of the impact zone became similar or even higher than RIs observed in the control zone, although the trees were relatively old. The finding demonstrates a high adaptive potential of *P. sylvestris* growing at the northern limit of pine forest distribution. The duration of the positive response to lower pollutant emission and the mechanisms activating the growth processes in the given conditions require further research.

FUNDING

This work was funded by the state research assignment to the Forest Research Institute (Karelian Research Center, Russian Academy of Sciences) and the Pasvik Nature Reserve and supported by the Kola Mining and Metallurgical Company and the Research and Educational Center "Russian Arctic: New Materials, Technologies, and Research Methods."

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Lukina, N.V. and Nikonov, V.V., *Biogeokhimicheskie tsikly v lesakh Severa v usloviyakh aerotekhnogennogo zagryazneniya* (Biogeochemical Cycles in the Northern Forests under Aerotechnogenic Pollution), Apatity, 1996, Part 2.
2. Yarmishko, V.T., Ignateva, O.V., and Evdokimova, A.S., Some aspects of Scots pine forests monitoring in extreme conditions of the Kola North, *Samar. Nauchn. Vestn.*, 2019, vol. 8, no. 2, pp. 81–86. https://doi.org/10.17816/snv201982115
3. Ananyeva, S.I., Belova, E.A., Bulychev, A.G., Bulycheva, I.A., Zakoldayeva, A.A., Zatsarinny, I.V., Isaeva, L.G., Kosyakova, A.Yu., Larkova, M.S., Lukina, N.V., Mershchiev, A.V., Polikarpova, N.V., Trushchitsina, O.S., Sobchuk, I.S., Sukhareva, T.A., and Khlebosolova, O.A., *Kol'skaya gorno-metallurgicheskaya kompaniya (promyshlennye ploshchadki "Nikel'" i "Zapolyarnyi"): vliyanie na nazemnye ekosistemy* (Kola Mining and Metallurgical Company (Industrial Sites "Nickel" and "Zapolyarny"): Impact on Terrestrial Ecosystems), Ryazan, 2012.
4. Usolstev, V.A., Vorobeichik, E.L., Khantemirova, E.V., Bergman, I.E., and Urazova, A.F., Studying forest biological productivity along industrial pollution gradients: methodical analysis and outlooks, *Vestn. Povolzh. Gos. Tekhnol. Univ.*, 2009, vol. 2, pp. 67–76. https://journals.volgatech.net/forest/article/view/368
5. Yarmishko, V.T., *Sosna obyknovennaya i atmosfernoe zagryaznenie na Evropeiskom Severe* (Scots Pine and Atmospheric Pollution in the European North), St. Petersburg, 1997.
6. Kozlova, L.N. and Onuchin, A.A., Influence of pollution on transpiration and structure of pine needles in the Nazarovskaya Hollow, in *Materialy konferentsii "Anatomiya, fiziologiya i ekologiya lesnoj rastitel'nosti"* (Proc. Conf. "Anatomy, Physiology and Ecology of the Forest Vegetation"), 1992, pp. 67–69.
7. Kaibiyainen, L.K. and Bolondinsky, V.K., Photosynthetic CO_2 fixation and biomass of the arboreal cenosis: method of estimating of CO_2 sequestering, *Fiziol. Rast.*, 1995, vol. 42, no. 1, pp. 138–143. https://www.elibrary.ru/item.asp?id=21837990
8. Vaganov, E.A. and Shashkin, A.V., *Rost i struktura godichnykh kolets hvoinykh* (Growth and Tree Ring Structure of Conifers), Novosibirsk, 2000.
9. Polyakova, G.R. and Urazgildin, R.V., Influence of technogenic pollution on dendrochronological parameters of Scots pine (*Pinus sylvestris* L.), *Byull. Chelyab. Gos. Univ.*, 2013, vol. 7, no. 298, pp. 191–194. https://www.elibrary.ru/item.asp?id=18958162
10. Rumyanstev, D.E., *Istoriya i metodologiya lesovodstvennoi dendrokhronologii* (History and Methodology of Silvicultural Dendrochronology), Moscow, 2010. https://mf.bmstu.ru/info/science/dendro/books/01.pdf
11. Kirdyanov, A.B. and Vaganov, E.A., Separation of the climatic signal reflected in variabe width and density of annual tree rings, *Lesovedenie*, 2006, vol. 6, pp. 71–75. https://www.elibrary.ru/item.asp?id=9309592
12. Shchekalev, R.V. and Tarkhanov, S.N., *Radial'nyi prirost i kachestvo drevesiny sosny obyknovennoi v usloviyakh atmosfernogo zagryazneniya* (Radial Growth and Quality of Scots Pine Wood under Atmospheric Pollution), Yekaterinburg, 2006.
13. Usoltsev, V.A., Vorobejchik, E.L., and Bergman, I.E., *Biologicheskaya produktivnost' lesov Urala v usloviyakh tekhnogennogo zagryazneniya: Issledovanie sistemy svyazei i zakonomernostei* (Biological Productivity of Ural Forests under Air Pollution: Investigation of System Interrelations and Patterns), Yekaterinburg, 2012.
14. Amineva, K.Z., Urazgildin, R.V., and Kulagin, A.Yu., Radial increment of pedunculate oak (*Quercus robur* L.) stem wood under anthropogenic pollution, *Bios-*

fera, 2014, vol. 6, no. 4, pp. 388–399. https://doi.org/10.24855/biosfera.v6i4.184

15. Vaganov, E.A., Skomarkova, M.V., Schulze, E.-D., and Linke, P., Variability of the structure and isotope composition of tree rings in *Pinus cembra* and *Picea abies* in the mountains of Northern Italy, *Lesovedenie*, 2007, vol. 3, pp. 32–39. https://www.elibrary.ru/item.asp?id=9510703
16. Yarmishko, V.T., Borisova, O.V., and Yarmishko, M.A., Long-term dynamics of the state of southern taiga forests under conditions of industrial atmospheric pollution, in *Dinamika lesnykh soobshchestv Severo-Zapada Rossii* (Dynamics of Forest Communities in North-West Russia), St. Petersburg, 2009, pp. 120–156.
17. Tishin, D.V., *Dendroekologiya (metodika drevesno-kol'tsevogo analiza* (Dendroecology (the Tree Ring Analysis Techniques), Kazan, 2011.
18. Mulgauzen, D.S. and Pankratova, L.A., The influence of aerotechnogenic pollution on Scots pine's radial growth in Kola North, *Vestn. S.-Peterb. Gos. Univ.,* 2016, vol. 7, no. 4, pp. 124–133. https://escjournal.spbu.ru/article/view/1827/2493
19. Alekseev, V.A., Diagnostics of tree vitality and stand condition, *Lesovedenie,* 1989, vol. 4, pp. 51–57.
20. Cybis Dendrochronology. Cybis Elektronik & Data AB. https://www.cybis.se.
21. Shiyatov, S.G., *Dendrohronologiya verhnei granitsy lesa na Urale* (Tree Line Dendrochronology in the Urals), Moscow, 1986. https://www.elibrary.ru/item.asp?id=22426951
22. Demakov, Yu.P. and Andreev, N.V., Patterns of radial growth of pine trees in the lakeside biotopes of the Mariy Chodra National Park, *Eko-Potentsial*, 2014, vol. 3, no. 7, pp. 48–58. https://elar.usfeu.ru/handle/123456789/3550
23. Nikolaeva, S.A. and Savchuk, D.A., Comprehensive approach and methods for the growth reconstruction and development of trees and forest community, *Vestn. Tomsk. Gos. Univ., Biol.*, 2009, vol. 2, no. 6, pp. 111–125. http://journals.tsu.ru/biology/&journal_page=archive&id=746&article_id=17408
24. Specialized Datasets for Climatic Studies. 2000-2011-20018-2022. RIHMI-WDC. http://meteo.ru/data
25. Gordeev, A.V., Kleshchenko, A.D., Chernyakov, B.A., and Sirotenko, O.D., *Bioklimaticheskii potentsial Rossii: teoriya i praktika* (Bioclimatic Potential of Russia: Theory and Practice), Moscow, 2006.
26. Lebedenko, L.A., Dynamics of the cambial cells reproduction in pine and spruce, in *Lesovosstanovleniye na Severo-Zapade RSFSR* (Forest Restoration in the Northwest of the RSFSR), Leningrad, 1978, pp. 101–111.
27. The R Project for Statistical Computing. The R Foundation. https://www.R-project.org/
28. Chernenkova, T.V., *Reaktsiya lesnoi rastitel'nosti na promyshlennoye zagryazneniye* (Response of Forest Vegetation to Industrial Pollution), Moscow, 2002.
29. Kaibiyainen, L.K., Safronova, G.I., and Bolondinskiy, Effect of toxic pollutants on the respiration of needles and shoots in Scots pine, *Russ. J. Ecol.*, 1998, vol. 29, no. 1, pp. 20–23.
30. Vitinsky, Yu.I., Kopetskiy, M., and Kuklin, G.V., *Statistika aktivnosti solnechnykh pyaten* (Statistics of Sunspot Activity), Moscow, 1986.
31. Matveev, S.M. and Rumyantsev, D.E., *Dendrokhronologiya* (Dendrochronology), Voronezh, 2013. https://mf.bmstu.ru/info/science/dendro/books/02.pdf
32. Timofeev, V.P., Seasonal tree growth duration and intensity as indicators of plantation productivity, in *Pitanie drevesnykh rastenii i povyshenie produktivnosti lesa* (Nutrition of Woody Plants and Forest Productivity Enhancement), Petrozavodsk, 1972, pp. 111–123.
33. Antonova, G.F., *Rost kletok khvoinykh* (Cellular Growth in Conifers), Novosibirsk, 1999. https://www.rfbr.ru/rffi/ru/books/o_61101
34. Vaganov, E.A., Shiyatov, S.G., and Mazepa, V.S., *Dendroklimaticheskie issledovaniya v Uralo-Sibirskoi Subarktike* (Dendroclimatic Study in Ural-Siberian Subarctic), Novosibirsk, 1996. https://ipae.uran.ru/sites/default/files/publications/ipae/1179_1996_VaganovEtAl.pdf
35. Barzut, O.S. and Staritsyn, V.V., On the influence of climatic factors on the radial growth of common juniper, in *Ekologicheskie problem Arktiki i severnykh territorii* (Environmental Problems of the Arctic and Northern Territories), Arhangel'sk, 2012, vol. 15, pp. 6–11. https://narfu.ru/lti/departments/kezl/Vypusk%2015.pdf
36. Barzut, V.M., Analysis of long-term and annual dynamics of coniferous growth in the White Sea region, *Extended Abstract of Cand. Sci. (Biol.) Dissertation*, Tartu, 1985.
37. Mulgauzen, D.S. and Pankratova, L.A., Radial growth of Scots pine in the area affected by mining and metallurgical combine 'Pechenganickel', *Vestn. Voronezh. Gos. Univ., Ser: Geogr. Geoecol.*, 2018, vol. 2, pp. 87–95. https://journals.vsu.ru/geo/article/view/2217
38. Khlebosolov, E.I., Makarova, O.A., Khlebosolova, O.A., Polikarpova, N.V., and Zatsarinniy, I.V., *Ptitsy zapovednika Pasvik* (Birds of the Pasvik Nature Reserve), Ryazan, 2007. http://oopt.aari.ru/ref/1004
39. Kucherov, S.E. and Muldashev, A.A., Radial increment of Scots pine in the vicinity of the Karabash copper smelter, *Lesovedenie*, 2003, vol. 2, pp. 43–49. http://lesovedenie.ru/index.php/forestry/article/view/37
40. Shchekalyov, R.V., Tarkhanov, S.N., Prozherina, N.V., and Klochikhin, A.N., Productivity of pine stands at the mouth of the Northern Dvina under conditions of long-term aerotechnogenic impact, *Materialy mezhdunarodnoi konferentsii "Problemy fiziologii rastenii Severa"* (Proc. Int. Sci. Conf. "Problems of the Physiology of the Northern Plants"), Petrozavodsk, 2004.

Translated by T. Tkacheva

Publisher's Note. Pleiades Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.