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SCOTS PINE (*PINUS SYLVESTRIS* L.) RADIAL INCREMENT FORMATION DUE TO CLIMATIC AND ANTHROPOGENIC FACTORS

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Abstract. The results of dendrochronological investigation of Scots pine (*Pinus sylvestris* L.) growth and condition in the impact zone of one of the biggest air pollution sources in Lithuania – cement plant "Akmenės cementas" are presented. Conifers are especially sensitive to environmental pollution. As an anatomical indicator of tree state, annual radial increment of trees was examined. The dynamics of annual radial increment is influenced by the main climatic parameters (air temperature and amount of precipitation) as well as an environmental pollution. The main attention was concentrated to assessment of the complex impact of climatic factors and industrial pollution on the radial increment of pine stands growing at different distances from the plant. Results of investigation and climate response models have shown that closest pine stands have suffered the strongest pollution impact, while the furthest pine stands were affected only by natural factors.

Keywords: dendrochronological investigation, Scots pine, annual radial increment, environmental pollution, climatic factors, complex impact.

1. Introduction

Forest ecosystems cover one third of land and produce almost two thirds of organic material, therefore they condition ecosphere substantially. Forests are important ecologically and environmentally – the accumulation role of the forests in the CO_2 balance is exclusive.

Trees are considered one of the most sensitive indicators of the environmental condition from all life forms. They are most suitable for the evaluation of environmental changes. Due to the structure of crown trees have better contact with the atmosphere, so they filter the flowing air mass better than other vegetation forms and consequently indicate the state of the forest ecosystems by anatomical and morphological symptoms. Trees determine the processes in the ecosphere and react sensitively to the impact of anthropogenic factors. Therefore they reflect the impact of climate and pollution integrally. The growth and productivity of trees as the main components of the forest ecosystems are among the best indicators, reflecting general forest condition and ecological balance. Objective evaluation of health condition of trees allows us to judge about the environmental quality and its suitability for prosperity of other life forms [18, 19].

Forest ecosystems growing close to the pollution source suffer the greatest impact, because the concentration of harmful materials often exceeds the permissible limits in the zone of local pollution. The extent of damage of the trees is determined by the concentration of pollutants as well as the duration of their impact. The increase of the amount of certain pollutants and the change of growing conditions in the polluted surroundings affect forests directly, cause various morphological, physiological and chemical changes, which result is the slow down of tree growth, decline of its condition or even death.

Tree ring width and structure is an important indicator of environmental pollution [11, 18]. During dendrochronological and dendroindicational research it was found that tree ring width and structure is highly dependent on climate variations and technogenic environmental pollution [11, 12, 17, 18] as well as on habitat conditions, microrelief, tree species, individual characteristics of trees. Therefore tree rings, their width and structure, integrally reflect the impact of all environmental factors by accumulating the information about environmental processes during the growth and are excellent indicators of the changes of environmental condition.

Trees are affected by a complex of factors, which are interconnected and strengthen each others' impact. Therefore complex impact of factors on tree growth and condition instead of that of separate factors (climate factors or anthropogenic pollution) is often the object of the dendrochronological investigations.

The objectives of investigation presented in this article were to analyse the impact of climatic factors on the formation of annual radial increment of pines in relatively clean environment; to determine possible effects of local pollution on annual radial increment and to investigate the complex impact of climatic factors and industrial pollution on the radial growth of pine stands in the zone of local pollution.

2. Materials and methods

Scots pine (*Pinus sylvestris* L.) stands in the surroundings of the cement plant "Akmenės cementas" at different distances from the pollution source were chosen as the objects of investigation. This tree species was chosen because it is the most widespread tree species in Lithuania, and forests, where this species dominates, comprise 36.2 % of total forest area.

"Akmenės cementas" is situated in the northern part of Lithuania. It began operating in 1952. In the beginning of the 1970s the plant emitted 27 thou. tons of SO_2, 9-10 thou. tons of cement dust, 8.5 thou. tons of NO_x and 1 thou. tons of ashes and other solid particles into the atmosphere annually [1] (Fig 1). In the beginning of the 1990s due to the industrial decline and modernization of technologies emissions decreased gradually. In 1989-1991 the emissions amounted to 60-70 thou. tons and dropped to approximately 3 thou. tons in recent years.

Research has been performed in 65-80-year-old pine stands of *Vaccinio-myrtillo-Pinetum* forest type at different distances (up to 5 km, 5-10 km and further than 10 km) from the plant in the direction of prevailing winds. Extent of the research is 20 sample plots, where 548 trees were evaluated (28 trees on average in each sample plot). Non-fertile and acidic (pH 3.5) drained peat-bog soils dominate in the investigated sites (D_t).

Methods of tree ring analysis. Annual radial increment was chosen as the main indicator of tree condition and its changes. Wood samples from selected pines of I and II class according to Kraft's classification were taken by Pressler's borer in each sample plot at 1.3 m height from root collar. Dry wood samples were soaked in water for 2-4 hours, so that annual rings regain their former width. To make the contours of early and late wood more visible, one side of the sample was cut by a special knife. For annual radial increment measurement and tree ring structure assessment LINTAB tree-ring measuring table and WinTSAP 0.30 computer program (F. Rinn Engineering Office and Distribution, Heidelberg) were used. Tree ring widths were measured with accuracy of 0.001 mm.

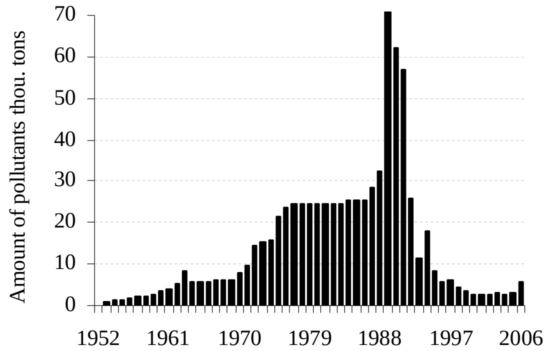

Fig 1. Total annual emissions of "Akmenės cementas" plant in 1952-2006

Synchronization of annual radial increment series. Dating quality and synchronity of radial increment series were evaluated by COFECHA 3.00P program from the IRTDB (International Tree Ring Date Bank) Program Library (R. L. Holmes, Tucson) [8]. Tree ring series or their parts with asynchronous growth were eliminated from the next stages of analysis (10 % on average in each plot).

Indexation of annual radial increment series. The width of tree rings depends not only on climate but also on other environmental factors: forest fires, diseases, stand density, tree crown and its changes, tree competition in the stand [4]. Tree age also influences the width of tree rings: rings of a young tree are relatively wide and rings of an older tree are narrower [6, 18]. Annual radial increment data standardisation was carried out by CHRONOL program [8] in order to eliminate the tree age influence on radial increment and to reveal the increment dynamics depending on climate variation. By using a negative exponential curve the age curve was removed.

Statistical data analysis. Pearson correlation analysis [7] was applied for the determination of relations between radial increment and climatic as well as anthropogenic factors. Multiple regression analysis was used to determine the factors causing the changes of radial increment and to evaluate the extent of these changes.

3. Results and discussion

3.1. Influence of air temperature and precipitation on the formation of annual radial increment

Dynamics of tree radial increment is determined not only by ecological conditions of the habitat and biological characteristics of tree species, but also by the long-term variation of climatic factors which is dominating [3, 19]. Sinchronity and periodicity of annual radial increment give evidence of rhythmical variation of climatic factors, which influences tree growth either positively or negatively, depending on the phase of the cycle [18].

Control stand with analogical biometric indices growing in relatively unpolluted environment 12 km south-west from the plant was chosen for the determination of relations between radial increment and climatic factors. According to literature [2, 11, 13, 16, 18], last year's climate conditions also have influence on tree growth and formation of radial increment. Therefore long-term air temperature and precipitation data of last year's January-December and current year's January-September were used in the analysis. Radial increment indices were calculated for the elimination of age influence on tree rings and in order to reveal increment dynamics due to variation of climate conditions. Increment indices were used in this and further analysis.

Radial increment relations with climatic factors usually are relatively weak (correlations don't exceed 0.3-0.4 in most cases) [10, 11]. Correlation analysis has shown statistically significant positive correlation between radial increment and precipitation of current year's January (r=0.37; p<0.05), and negative correlation with July's precipitation (r=-0.25; p<0.05) (Fig 2). Positive and statistically significant correlation was found between radial increment and mean temperatures of spring (April-May) and June (r=0.22-0.34; p<0.05).

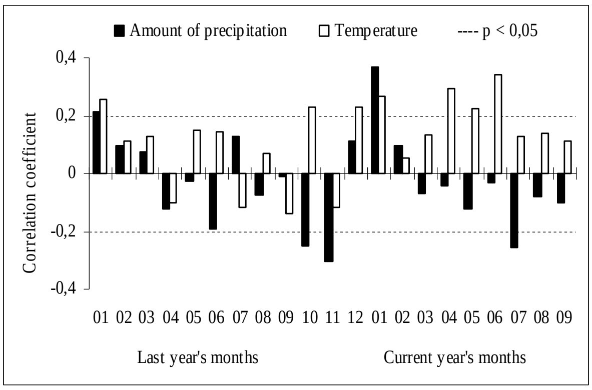

Fig 2. Pearson correlations between annual radial increment of control pine stands and climatic factors

Analysis has revealed significant influence of last year's climate conditions on the formation of radial increment. Statistically significant relations were found between radial increment and air temperature as well as precipitation of last January (r=0.26 and r=0.21 respectively; p<0.05). Radial increment correlated negatively with precipitation of last October and November (r=-0.25 and r=-0.31 respectively; p<0.05) and positively with temperatures of last October and December (r=0.23; p<0.05). This corresponds with the results obtained by other authors [10, 11, 18] showing strong influence of last autumn's climate conditions.

Results suggest that air temperature and precipitation of the period of active vegetation are important to the radial increment formation in boggy soils. Higher temperature of active vegetation period (April-August) and precipitation lower than long-term average cause drying processes in the habitat and stimulate the formation of radial increment. Summer precipitation higher than long-term average and the shortage of warmth in the beginning of vegetation period induce habitat's bogging processes, which cause significant decrease of radial increment.

3.2. Relations between annual radial increment of pines growing at different distances from the plant and amount of emissions

In order to estimate possible industrial pollution effect on the radial increment of pines growing near "Akmenės cementas" plant, firstly it was analysed whether differences between increment series (Fig 3) are statistically significant or have an accidental nature. Statistical hypothesis H_0 (means of radial increment series from pines at different distances from the pollution source do not differ) with an alternative H_1 (at least two means differ) was formulated for the analysis. The value of Fisher's criterion F indicating statistically significant differences between the means of data groups equals to 41.36. This value $F = 41.36 > F_{cr}$ ($F_{cr} \approx 3$), where F_{cr} is critical F value at significance α =0.05 [7]. According to the rules of ANOVA this denies hypothesis H_0 and shows that the means of at least two radial increment series differ statistically significantly. This suggests that the cause of these differences is an external factor – environmental pollution.

Pairwise comparison of the series was performed using Fisher's LSD (*Least Significant Difference*) criterion, which corresponds to the *T*-test (Student's criterion *t*). It was determined that series mean from pines closest to the plant is statistically significantly less than that of pines at 5-10 km from the plant ($t = -5.0 < -t_{cr}$; $t_{cr} = 1.66$) and series mean of pines at 5-10 km is statistically significantly less than that of the most distant pines ($t = -4.63 < t_{cr}$; $t_{cr} = 1.66$). This proves that radial increment increases with distance from the plant.

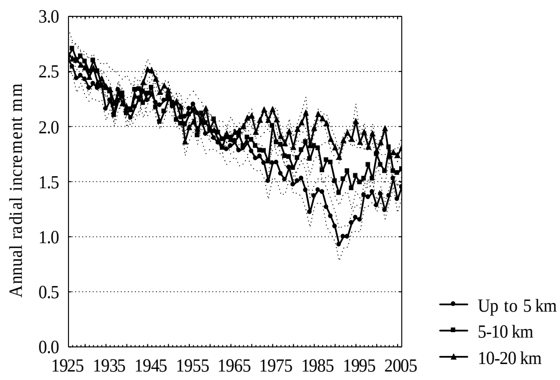

Fig 3. Annual radial increment series of the investigated pine stands

Dispersion analysis results (Fisher's and Student's criterions) suggest that differences of radial increment of pines growing at different distances from the plant are possibly caused by local pollution.

In order to clarify possible reasons for radial increment changes, relationships between radial increment of pines and amount of plant's emissions were analysed.

The strongest negative relation was found between radial increment of pines closest to the plant and total amount of pollutants (r=-0.62; p<0.05) (Table 1). Correlations between total amount of pollutants and radial increment of pines at the distance of up to 5 km and 5-10 km from the plant are strong and statistically significant (r=-0.62 and r=-0.49 respectively; p<0.05). No significant relations were found between radial increment of the most distant pines and amount of pollution (p>0.05).

Table 1. Pearson correlations between annual radial increment and emissions during the pollution period (r – Pearson correlation coefficient, p – significance)

	Total emissions	Solid particles	NO_x	SO_2
	1952-2005			
Up to 5 km				
r value	**-0.62**	**-0.62**	**-0.55**	**-0.65**
p value	0.000	0.000	0.000	0.000
5-10 km				
r value	**-0.49**	**-0.49**	**-0.42**	**-0.55**
p value	0.000	0.000	0.002	0.000
10-20 km				
r value	-0.16	-0.15	-0.15	-0.17
p value	0.2	0.2	0.3	0.2

Note. Statistically significant r values (p<0.05) are shown in bold characters.

Correlation analysis has revealed that amount of SO_2 and solid particles could have the strongest influence to the variation of radial increment of the closest (up to 5 km) pines (r=-0.65 and r=-0.62 respectively; p<0.05). Slightly weaker correlations were found with the amount of NO_x emissions (r=-0.55; p<0.05). At the distance of 5-10 km from the plant correlations between radial increment and pollution components were weaker but statistically significant. Like for the first distance, statistically significant correlations were found between radial increment and amount of SO_2, solid particles and NO_x (r equals to -0.55; -0.49 and -0.42 respectively; p<0.05). Correlations between radial increment of the most distant pines and total emissions and their components became statistically insignificant (p>0.05).

3.3. Complex impact of climatic factors and industrial pollution on the radial growth

The change of tree condition isn't caused by one certain factor. Trees are affected by a complex of factors, which are interdependent and strengthen each others' impact [5, 9, 14]. The aim of dendrochronological investigations often is not one factor's (climate or pollution) impact but their complex impact on radial increment. For this purpose multiple regression models are constructed, describing radial increment variation dependence on both climatic and anthropogenic factors [2, 12, 15, 20].

The results of correlation analysis have shown that radial increment of pines growing at different distances from the plant suffer different impact of solid particles, NO_x and SO_2 emissions. Firstly multiple regression models based only on pollution components were constructed. The form of function used for the formation of the models is:

$$y = a + b_1 x_1 + b_2 x_2 + ... + b_k x_k \quad (1)$$

where: y – the dependent variable; x – the independent variable; a and b – non-standardized regression coefficients.

Non-standardized b coefficients do not allow the intercomparison of the variables and determination of their relative relevance when calculating y values, because the magnitude of b depends on the dimension of x_i and the scatter of data. Relative influence of independent variables (pollution components) to the dependent variable (annual radial increment) is described by the standardized regression function coefficients β. The greater the absolute value of β, the stronger y dependence on x_i [7].

Regression model including the main components of "Akmenės cementas" plant emissions (solid particles (KD_{10}), NO_x and SO_2) explains 62 % of radial increment variation (R^2 =0.62) (Fig 4).

The standardized coefficients β show that negative influence of solid particles is most relevant (β =-0.81; p =0.002), and the least important is the influence of SO_2 (β =-0.42; p =0.04). The influence of NO_x is positive (β =0.55; p =0.002).

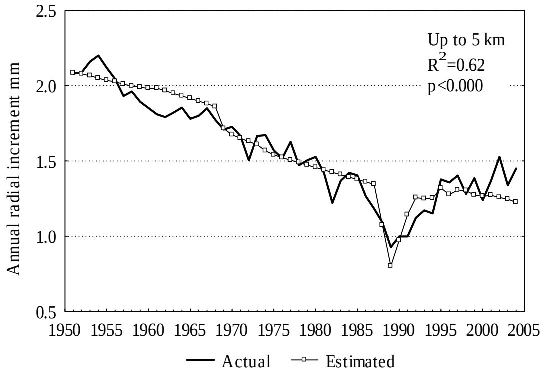

Fig 4. Dynamics of actual and estimated annual radial increment of stands growing up to 5 km from the plant during the pollution period

$$P_t = (-3.45 + 5.99*\exp(-0.003*t))\,(102.85 - 2.57\,KD_{10} + 4.04\,NO_x - 2.33\,SO_2)$$

Standardized coefficients:

β (KD_{10})=-0.81 (p=0.002)
β (NO_x)=0.55 (p=0.002)
β (SO_2)=-0.42 (p=0.04)

Where: P_t – tree ring width (mm); t – tree age (years); KD_{10} – amount of solid particles (thou. t); NO_x – amount of nitrogen oxides (thou. t); SO_2 – amount of sulphur dioxide (thou. t).

The dependence of tree increment on emissions decreases with increase of distance from the pollution source. It was determined that approximation level of regression model including only NO_x and SO_2 (influence of KD_{10} becomes insignificant) is only R^2 =0.36 for the distance of 5-10 km. For the stands at 10-20 km from the plant the dependence becomes statistically insignificant (p >0.05).

As it was mentioned, changes of tree radial increment depend not only on air pollution, but on climatic factors as well. In order to approximate the changes of radial increment more exactly, values of climatic factors (month's mean air temperature and amount of precipitation) were included into multiple regression models additionally.

After inclusion of climatic factors into the model, the approximation level of radial increment variation improves (R^2 =0.70) (Fig 5). However, the influence of pollution components is stronger than that of climatic factors. Relevance of solid particles remains the strongest (β =-0.75; p =0.002).

The standardized coefficients β show that influence of climatic factors (air temperature of last year's August (β =0.24; p =0.01) and November (β =-0.18; p =0.04) and precipitation of current year's July (β =0.24; p =0.03)) on the radial increment is less than that of pollution components but statistically significant.

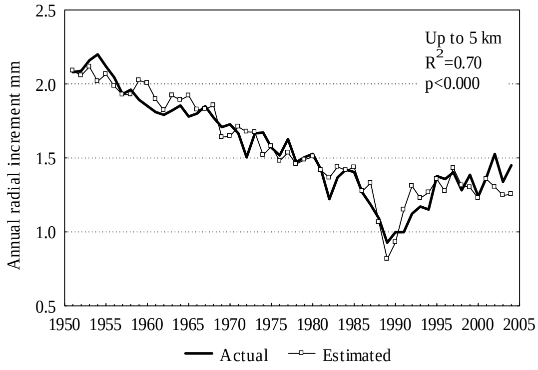

Fig 5. Dynamics of actual and estimated annual radial increment of stands growing up to 5 km from the plant during the pollution period

Standardized coefficients:

β ($T_{Aug_{t-1}}$)=0.24 (p =0.01)
β ($T_{Nov_{t-1}}$)=-0.18 (p =0.04)
β (P_{Jul_t})=-0.19 (p =0.03)
β (KD_{10})=-0.75 (p =0.002)
β (NO_x)=0.57 (p =0.001)
β (SO_2)=-0.47 (p =0.02)

Where: P_t – tree ring width (mm); t – tree age (years); P – month's amount of precipitation (mm); T – month's mean air temperature (°C); KD_{10} – amount of solid particles (thou. t); NO_x – amount of nitrogen oxides (thou. t); SO_2 – amount of sulphur dioxide (thou. t).

Approximation level R^2 decreases with distance from the pollution source (Fig 6). Complex regression model based on climatic factors and pollutants describes 57 % (R^2 =0.57) of radial increment variation of pines growing at the distance of 5-10 km from the plant.

As it is seen in presented regression model, solid particles are eliminated from the model (their influence becomes insignificant; p >0.05) and the emissions of SO_2 become more relevant (β =-0.97; p =0.000).

In the given regression model influence of last November's temperature gets stronger (β =-0.28;

p=0.01), and influence of new factors emerge – temperature of last October (β=0.24; p=0.02) and current year's September (β=0.23; p=0.02) as well as precipitation of current year's August (β=-0.21; p=0.04).

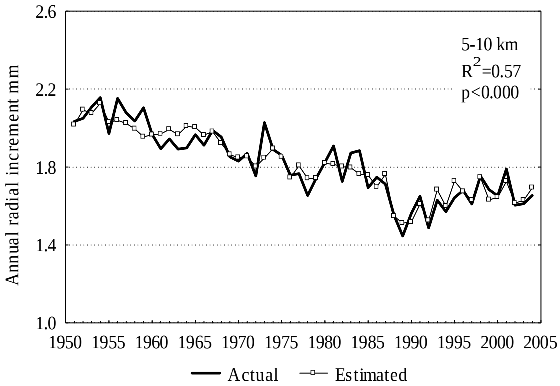

Fig 6. Dynamics of actual and estimated annual radial increment of stands at the distance of 5-10 km from the plant during the pollution period

$$P_t = (1.41 + 1.29\text{*}\exp(-0.02\text{*}t))\ (86.82 + 0.81\,T_{Oct_{t-1}} - 0.66\,T_{Nov_{t-1}} - 0.02\,P_{Aug_t} + 0.79\,T_{Sep_t} + 2.06\,NO_x - 2.3\,SO_2)$$

Standardized coefficients:

β ($T_{Oct_{t-1}}$)=0.24 (p=0.02)
β ($T_{Nov_{t-1}}$)=-0.28 (p=0.01)
β (P_{Aug_t})=-0.21 (p=0.04)
β (T_{Sep_t})=0.23 (p=0.02)
β (NO_x)=0.66 (p=0.000)
β (SO_2)=-0.97 (p=0.000)

Where: P_t – tree ring width (mm); t – tree age (years); P – month's amount of precipitation (mm); T – month's mean air temperature (°C); NO_x – amount of nitrogen oxides (thou. t); SO_2 – amount of sulphur dioxide (thou. t).

Only climatic factors remain in regression model for the radial increment of the most distant pine stands (Fig 7). This shows that pine stands at the biggest distance from the plant are influenced only by natural factors. Model reveals the importance of climatic conditions of last year's autumn. Influence of last October's temperature (β=0.23) and precipitation (β=-0.39) as well as influence of last November's temperature (β=-0.42) are statistically significant (p<0.05).

Regression model based only on climatic factors explains 51 % of annual radial increment variation (R^2=0.51).

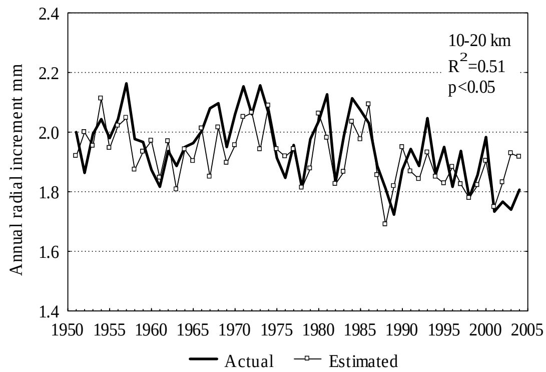

Fig 7. Dynamics of actual and estimated annual radial increment of stands at the distance of 10-20 km from the plant during the pollution period

$$P_t = (1.79 + 0.82\text{*}\exp(-0.03\text{*}t))\ (123.77 - 0.05\,P_{Oct_{t-1}} + 0.83\,T_{Oct_{t-1}} - 0.81\,T_{Nov_{t-1}} + 0.8\,T_{May_t} + 0.42\,T_{Sep_t})$$

Standardized coefficients:

β ($P_{Oct_{t-1}}$)=-0.39 (p=0.001)
β ($T_{Oct_{t-1}}$)=0.23 (p=0.03)
β ($T_{Nov_{t-1}}$)=-0.42 (p=0.001)
β (T_{May_t})=0.31 (p=0.01)
β (T_{Sep_t})=0.29 (p=0.01)

Where: P_t – tree ring width (mm); t – tree age (years); P – month's amount of precipitation (mm); T – month's mean air temperature (°C).

Analysis results confirm the hypothesis that variation of radial increment of pines in the impact zone of the plant is determined by the complex impact of climatic factors and pollution, and the impact of pollutants on trees decreases with distance from the pollution source. Complex multiple regression models including climatic factors and pollution components approximate radial increment variations more exactly.

Several factors, such as temperature of last October, November and current year's September are included in more than one model and correspond to climatic factors which correlate with radial increment of control pine stands statistically significantly. This shows radial increment dependence on certain climatic factors, typical for that habitat.

4. Conclusions

1. Average air temperature of active vegetation period (April-August) higher than long-term average influences pine radial growth positively (r=0.22-0.34; p<0.05), and amount of precipitation in July higher than long-term average induces the decrease of radial increment (r=-0.25; p<0.05) in peat-bog soils.
2. Linear relation was determined between radial increment of pines close to the plant and plant

emissions: r=-0.62 for pines at the distance of up to 5 km and r=-0.49 for pines at the distance of 5-10 km (p<0.05). No linear relations were found between plant emissions and radial increment of the most distant pine stands (p>0.05).

3. Multiple regression model based only on the main components of plant's pollution explains 62 % (p<0.05) of radial increment variation of pines closest to the plant. Approximation level decreases with increasing distance from the plant (R^2=0.36 for the distance of 5-10 km) and for the most distant pine stands it becomes statistically insignificant (p>0.05).
4. Complex regression model including climatic factors and pollution components approximates radial increment more exactly: determination coefficient R^2=0.70 for the closest pine stands and R^2=0.57 for the stands at the distance of 5-10 km (p<0.05). Only climatic factors remain in regression model for the radial increment of the most distant pine stands.

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