Influence of Climatic and Anthropogenic Factors on the Radial Growth of Scots Pine (*Pinus sylvestris* L.)

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Abstract

The results of long-term 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 as cement plant "Akmenės Cementas" are presented. Conifers are especially sensitive to environmental pollution. As an anatomical indicator of anatomical indicator of tree vitality, annual radial increment of trees was examined. The dynamics of the annual radial increment is influenced by the main climatic parameters (air temperature and amount of precipitation) as well as 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.

Key words: dendrochronological investigation, Scots pine, annual radial increment, environmental pollution, climatic factors, synergistic impact

Introduction

Forest ecosystems cover one third of land and produce almost two thirds of organic material, therefore they influence ecosphere essentially. 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 features. Trees determine the processes in the ecosphere and react sensitively to the impact of anthropogenic factors. Therefore they integrate the impact of climate and pollution (Stravinskienė 2002, 2005).

Forest ecosystems growing close to the pollution source suffer the greatest impact, because the concentration of harmful materials often exceeds the permissible limits. The extent of damage on trees is determined by the concentration of pollutants as well as duration of their impact. An increase in the amount of certain pollutants and change of growing conditions in the polluted surroundings affect forests directly, cause various morphological, physiological and chemical changes, the result of which 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 (Innes 1993, Juknys *et al.* 2002, Stravinskienė 2002). During dendrochronological research it was found that tree-ring width and structure are highly dependent on climate variations and technogenic environmental pollution (Schweingruber 1996, Stravinskienė 2002, Juknys *et al.* 2002, 2003) as well as on habitat conditions, microrelief, tree species, and individual characteristics of trees. Therefore tree rings and their width and structure, integrally reflect the impact of all environmental factors by accumulating the information about environmental processes during the growth (Ozolinčius 1994), and are excellent indicators of the changes in environmental condition.

The objectives of investigation were to analyse the impact of climatic factors on the formation of the annual radial increment of pines in relatively clean environment; to determine possible effects of local pollution on the 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.

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. Pine was chosen because it is the most widespread tree species in Lithuania, and forests, where pine 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 thousand tons of SO_2, 9-10 thousand tons of cement dust, 8.5 thousand tons of NO_x, 1 thousand tons of ashes and other solid particles into the atmosphere annually (Armolaitis *et al.* 1999) (Figure 1). At 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 thousand tons and abated to approximately 3 thousand tons in recent years.

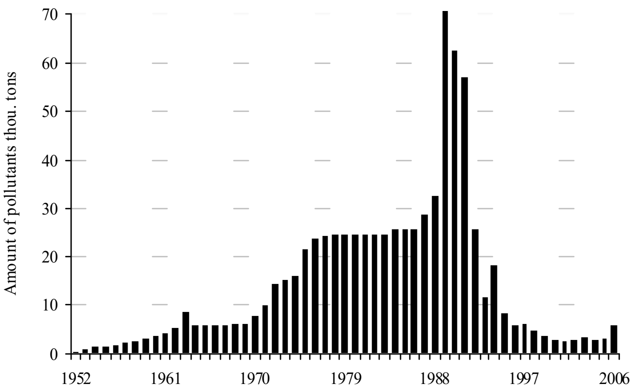


Figure 1. Total annual emissions of "Akmenės cementas" plant in 1952-2006

Research has been performed in the 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 on 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 a 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 latewood 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.

Synchronization of annual radial increment series. Dating quality and synchronity of radial increment series were evaluated by COFECHA 3.00P program from the ITRDB (International Tree Ring Data Bank) Program Library (R. L. Holmes, Tucson) (Holmes 1994). Tree-ring series or their parts with asynchronous growth were eliminated from the next stages of analysis (10 % on average in each sample 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, and tree competition in the stand (Bräker 1992, Schweingruber 1996). 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 (Cook *et al.* 1990, Stravinskienė 2002). Standardisation of annual radial increment data was carried out in order to eliminate the tree age influence on radial increment and to reveal the increment dynamics depending on climate variation. The age trend was removed by using a negative exponential curve.

Statistical data analysis. The chronologies of the radial increment at different distances from the plant were statistically compared by ANOVA (Fisher criterion *F*). Differences were considered statistically significant at $p<0.05$ ($F<F_{cr}$). In the cases of significant effects, the differences between each pair of chronologies were investigated by pairwise *t*-test for independent samples. Radial increment series *x* was considered statistically significantly less than radial increment series *y* at $p<0.05$ ($t<t_{cr}$) (Student's criterion) (Čekanavičius and Murauskas 2000, Venclovienė 2000). Pearson correlation analysis was applied for the determination of relations between the radial increment and climatic as well as anthropogenic factors. Multiple regression analysis (Čekanavičius and Murauskas 2002) was used to determine the factors causing the changes in the radial increment and to evaluate the extent of these changes. 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 (Čekanavičius and Murauskas 2002).

Results

Influence of air temperature and precipitation on the formation of annual radial increment. Control stand with analogical biometric characteristics growing in relatively unpolluted environment 12 km southwest from the plant was chosen for the determination of relations between the radial increment and climatic factors. Long-term air temperature and precipitation data of the last year's January-December and current year's January-September of Šiauliai meteorological station were used in the analysis. Šiauliai meteorological station is about 50 km away from the study area. 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.

Correlation analysis has shown statistically significant positive correlation between the 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) (Figure 2).

Positive and statistically significant correlation was found between the radial increment and mean temperatures of spring (April-May) and June (r=0.22-0.34; p<0.05). Statistically significant relations were found between the radial increment and air temperature as well as precipitation of last January (r=0.26 and r=0.21 respectively; p<0.05). The 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).

Relations between annual radial increment of pine growing at different distances from the plant and amount of plant emissions. Pine stands growing at different distances from the "Akmenės Cementas" plant were chosen for the investigation so that distance differences reveal possibly different environmental impact on tree growth. 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 (Figure 3) are statistically significant or have an accidental nature.

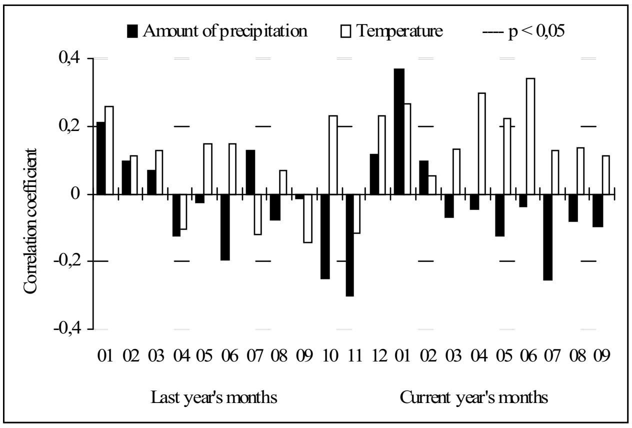


Figure 2. Pearson correlation between annual radial increment of control pine stands and climatic factors

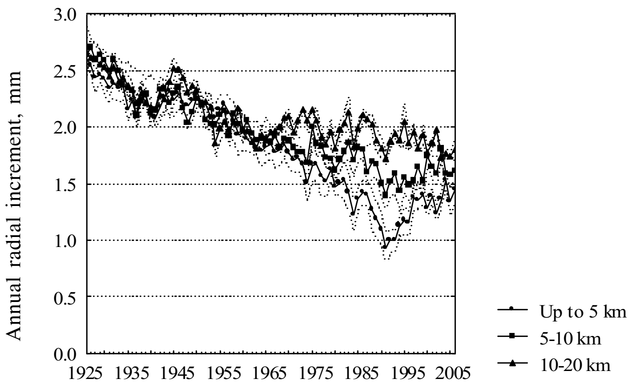


Figure 3. Annual radial increment series (solid lines) of the investigated pine stands at different distances from the pollution source. The dotted lines show 95 % confidence intervals

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 of radial increment series 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 (p<0.05). This value F= 41.36>F_{cr} , (F_{cr} ≈3) where F_{cr} is critical F value at significance α=0.05 (Čekanavičius and Murauskas 2002). 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 the radial increment increases with distance from the plant.

Dispersion analysis results (Fisher's and Student's criterions) suggest that differences of the 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 the radial increment of pines and amount of plant's emissions were analysed. The strongest negative relation was found between the radial increment of pines closest to the plant and total amount of pollutants (r=-0.62; p<0.05) (Table 1). Correlations between the 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 the radial increment of the most distant pines and amount of pollution (p>0.05).

Table 1. Pearson correlation between annual radial increment and emissions during the pollution period 1952-2005 (*r*– Pearson correlation coefficient, *p* – significance)

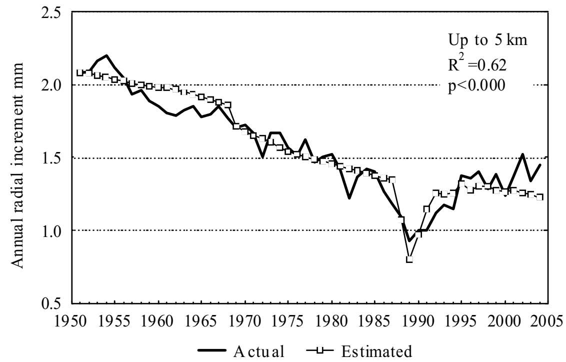
		Total emissions	Solid particles	NO_x	SO_2
		1952-2005			
Up to 5 km					
	r	**-0.62**	**-0.62**	**-0.55**	**-0.65**
	p	0.000	0.000	0.000	0.000
5-10 km					
	r	**-0.49**	**-0.49**	**-0.42**	**-0.55**
	p	0.000	0.000	0.002	0.000
10-20 km					
	r	-0.16	-0.15	-0.15	-0.17
	p	0.2	0.2	0.3	0.2

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 the 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 the radial increment and pollution components were weaker but statistically significant. Like for the first distance, statistically significant correlations were found between the radial increment and amount of, solid particles and (r equals to -0.55; -0.49 and -0.42, respectively; p<0.05). Correlations between the radial increment of the most distant pines and total emissions and their components became statistically insignificant (p>0.05).

Complex impact of climatic factors and industrial pollution on the radial growth. The results of correlation analysis have shown that the radial increment of pines growing at different distances from the plant suffer different impact of solid particles, and SO_2 emissions. Firstly, multiple regression models based only on pollution components were constructed. A 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) (Figure 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 (β=-0.42; p = 0.04). The influence of NO_x is positive (β = 0.55; p = 0.002).

The dependence of tree increment on emissions decreases with increase in distance from the pollution source. It was determined that approximation level of a regression model including only and (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).



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

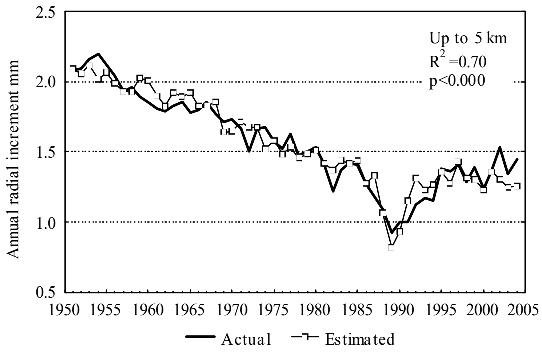
Standardized coefficients: β (KD_{10})=-0.81 (p=0.002)
β (NO_x)=0.55 (p=0.002)
β (SO_2)=-0.42 (p=0.04)

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).

Figure 4. Dynamics of actual and estimated annual radial increment of stands growing up to 5 km from the plant during the pollution period (regression model based on pollutants)

In order to approximate the changes in the 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 the radial increment variation improves (R^2=0.70) (Figure 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 showed 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.



$$P_t = (-3.45 + 5.99*\exp(-0.003*t))\,(67.08 + 1.98\,T_{Aug_{t-1}} - 0.97\,T_{Nov_{t-1}} - 0.06\,P_{Jul_t} - 2.39\,KD_{10} + 4.2\,NO_x - 2.63\,SO_2)$$

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)

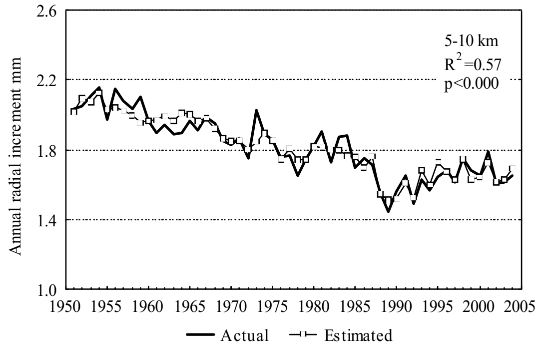
β (NO_x)=0.57 (p=0.001)

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 par ticles (thou. t); NO_X – amount of nitrogen oxides (thou. t); SO_2 – amount of sulphur dioxide (thou. t).

Figure 5. Dynamics of actual and estimated annual radial increment of stands growing up to 5 km from the plant during the pollution period (regression model based on climatic factors and pollutants)

The approximation level R^2 decreases with distance from the pollution source. A complex regression model based on climatic factors and pollutants describes 57 % (R^2=0.57) of the radial increment variation of pines growing at the distance of 5-10 km from the plant (Figure 6). As it is seen in the 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 this regression model the influence of last November's temperature gets stronger (β=-0.28; p=0.01), and the 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).



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

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).

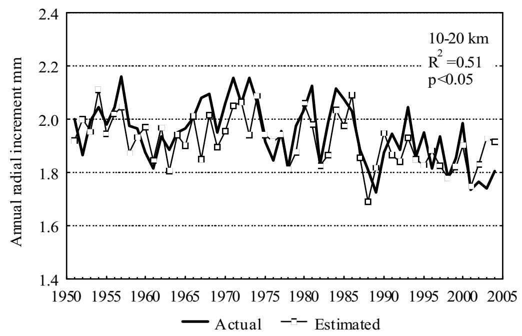
Figure 6. Dynamics of actual and estimated annual radial increment of stands at the distance of 5-10 km from the plant during the pollution period (regression model based on climatic factors and pollutants)

Only climatic factors remain in a regression model for the radial increment of the most distant pine stands (Figure 7). This shows that pine stands at the largest distance from the plant are influenced only by natural factors.

The model revealed the importance of climatic conditions of last year's autumn. The 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). The regression model based only on climatic factors explains 51 % of annual radial increment variation (R^2=0.51).

Discussion

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 (Bitvinskas 1997). Synchronity and periodicity of the annual radial increment gives evidence of rhyth-



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

Standardized coefficients:

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

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).

Figure 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 (regression model based on climatic factors)

mical variation of climatic factors, which influences tree growth either positively or negatively, depending on the phase of the cycle (Stravinskienė 2002). Although relations between the radial increment and climatic factors usually are relatively weak (coefficient of correlation does not exceed 0.3-0.4 in most cases) (Juknys and Venclovienė 1998, Juknys *et al.* 2002), results of the correlation analysis suggest that the air temperature and precipitation of the growing period are important to the radial increment formation in boggy soils. Higher temperature of the growing period (April-August) and precipitation lower than long-term average cause drying processes in the habitat and stimulate the formation of the radial increment. Summer precipitation higher than long-term average and the shortage of warmth at the beginning of the growing period induce habitat's paludification processes, which cause significant decrease in the radial increment. Similar tendencies were found in the studies of other authors (Kairiūkštis 1994, Stravinskienė 2002).

Analysis has revealed the significant influence of last year's climate conditions on the formation of the radial increment. This corresponds to the results obtained by other authors (Fritts 1976, Cook and Kairiūkštis 1990, Juknys and Venclovienė 1998, Linderholm 2001, Juknys *et al*. 2002, Stravinskienė 2002, Pederson *et al*. 2004, Augustaitis 2005) showing strong influence of last autumn's climate conditions.

The change of tree condition is not caused by one certain factor. Trees are affected by a complex of factors, which are interdependent and strengthen each others' impact (Innes 1993, Chappelka and Freer-Smith 1995, Nihlgard 1997). The aim of dendrochronological investigations often is not one factor's (climate or pollution) impact but their complex impact on the radial increment. For this purpose multiple regression models are constructed, describing the radial increment variation dependence on both climatic and anthropogenic factors (Ots and Rauk 1999, Juknys *et al.* 2003, Thompson 2003, Augustaitis 2005). Complex multiple regression models including climatic factors and pollution components approximate radial increment variations more exactly, and the impact of pollutants on trees decreases with distance from the pollution source.

Conclusions

1. Average air temperature of the growing 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 in the radial increment (r=-0.25; p<0.05) in peat-bog soils.

2. Linear relation was determined between the 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 the radial increment of the most distant pine stands (p>0.05).

3. A multiple regression model based only on the main components of plant's pollution explains 62 % (p<0.05) of the radial increment variation of pines closest to the plant. The 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. A complex regression model including climatic factors and pollution components approximates the 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 a regression model for the radial increment of the most distant pine stands.

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ВЛИЯНИЕ КЛИМАТИЧЕСКИХ И АНТРОПОГЕННЫХ ФАКТОРОВ НА РАДИАЛЬНЫЙ ПРИРОСТ СОСНЫ ОБЫКНОВЕННОЙ (*PINUS SYLVESTRIS* L.)

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Резюме

В статье представлены результаты долгосрочных дендрохронологических исследований, проведенных на приросте и состоянии сосны обыкновенной (*Pinus sylvestris* L.) в зоне воздействия одного из самых больших источников загрязнения воздуха в Литве – завода цемента "Акмянес цементас". Как анатомический индикатор состояния дерева исследован радиальный прирост. Главное внимание было сконцентрировано на оценке комплексного воздействия климатических факторов и индустриального загрязнения на радиальный прирост сосновых древостоев, растущих на различных расстояниях от завода. Установлено, что на динамику радиального прироста влияли климатические факторы (температура воздуха и осадки), а так же антропогенное загрязнение. Результаты функций отклика показали, что на близкие к заводу сосновые древостои обнаружено наиболее сильное воздействие загрязнения, в то время, как самые далекие сосновые древостои были подвергнуты только природным факторам.

Ключевые слова: дендрохронологическое исследование, сосна обыкновенная, радиальный прирост, загрязнение среды, климатические факторы, комплексное влияние