VYTAUTAS MAGNUS UNIVERSITY
LITHUANIAN FOREST RESEARCH INSTITUTE

Regina **ERLICKYTĖ**

REGULARITIES OF SCOTS PINE (*Pinus sylvestris* L.) RADIAL INCREMENT FORMATION DUE TO VARIATION OF EMISSIONS OF "AKMENĖS CEMENTAS" AND "ACHEMA" PLANTS

SUMMARY OF DOCTORAL DISSERTATION

BIOMEDICAL SCIENCES, ECOLOGY AND ENVIRONMENTAL SCIENCES (03 B)

KAUNAS, 2007

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VYTAUTO DIDŽIOJO UNIVERSITETAS
LIETUVOS MIŠKŲ INSTITUTAS

Regina Erlickytė

PAPRASTOSIOS PUŠIES (*Pinus sylvestris* L.) RADIALIOJO PRIEAUGIO FORMAVIMOSI DĖSNINGUMAI KINTANT „AKMENĖS CEMENTO“ IR „ACHEMOS“ TERŠALŲ IŠMETIMAMS

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INTRODUCTION

Relevance of the problem. 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 accumulational 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 the 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 condition of the forest ecosystems by anatomical and morphological symptoms. Trees determine the processes in the ecosphere and react sensitively to the 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 condition of trees allows us to judge about the environmental condition and its suitability for prosperity of other life forms (Stravinskienė, 2002, 2005).

Forest ecosystems growing close to the pollution sources suffer the greatest impact because the concentration of harmful materials in the local pollution zone often exceeds permissible amounts. The extent of damage to the trees is determined by the concentration of pollutants as well as the duration of their impact and their amount in the trees.

Significant damages of tree stands have been determined in different regions of north-western Europe. Most scientists state that decline of forest condition is caused by a complex of various factors, but the main factor causing large scale forest damage is environmental pollution, and other negative factors just strengthen the impact of pollutants (Bach, 1985; Innes, 1993; Chappelka, Freer-Smith, 1995; Nihlgard, 1997). Unfavourable climate conditions, invasions of forest pests, various diseases and forestry mistakes (Fuhrer, 1990; Auclair et al., 1992; Houston, 1992) are often mentioned together with different pollutants.

Local pollution sources have the strongest negative influence to forest ecosystems in Lithuania. One of the largest local pollution sources is nitrogen fertilizers plant "Achema", and forests growing in its local impact zone suffer the impact of acidifying and eutrophying pollutants. Heavy emissions of SO_2, NO_x, NH_3 and other pollutants caused the acidification of the surrounding forest soils and intensive decline of tree stands. After the decrease of emissions the process of forest ecosystems recovery began. However, results of recent forest ecosystem monitoring have shown that acidification of forest soils in the vicinity of the plant continues (Armolaitis, 1998; Armolaitis et al., 1999a; Armolaitis, Stakėnas, 2001).

The impact of technogenic dust on the vegetation was not given as much attention of the scientists as the impact of SO_2, NO_x or other pollutants. Although this problem is not new, the mechanism of impact, the character of reaction, vulnerability and tolerance of ecosystems have not been completely described so far. Alkalizing dust emitted by the "Akmenės cementas" plant neutralizes the acidifying pollutants (SO_2, NO_x) and alkalizes the environment.

Dendrochronological monitoring is being performed since the first years of forest monitoring in Lithuania. The information in tree rings is used for the indication of environmental condition. Anatomical structure of trees provides the unique possibility to retrospectively evaluate the variation of quantitative (the width of annual ring) and qualitative (the relation of late and early wood in the tree ring) changes of radial increment from the first year of growth till the year of investigation (Stravinskienė, 1995, 1997, 2002; Juknys et al., 2002). The dynamics of tree rings provides information about ecological and climatic conditions of the area and the local phenomena. Tree rings, their width and structure integrally reflect the complex impact of environmental factors (Lovelius, 1997). Dendrochronological indication, unlike other methods of bioindication, allows to evaluate the condition of the stand not only during the monitoring, but also retrospectively. Therefore the role of tree rings, as the indicator of environmental conditions, is important for the evaluation of environmental changes.

The research was based on the hypothesis that:

- variation of pine radial increment of stands growing in the local pollution zone is determined by the complex impact of climatic factors and pollution;
- after the reduction of industrial pollution its negative impact on the stands weakens, therefore the decrease of radial increment stabilizes, and recovery of stand growth begins.

The objective of the research was to analyse the changes of annual radial increment of pine stands (*Pinus sylvestris* L.) in the zones of local alkalizing, acidifying and eutrophying pollution and to determine the regularities of radial increment recovery after the decrease of pollution.

To achieve this objective the following **tasks** were set up:

- to analyse the impact of climatic factors on the formation of annual radial increment of pines in relatively clean environment;
- to determine the changes of annual radial increment of pines growing at different distances from the pollution source depending on the intensity of pollution;
- to investigate the complex impact of climatic factors and industrial pollution on the radial growth of pines;
- to evaluate the anthropogenic changes of radial increment under the impact of local pollution;
- to analyse the recovery processes of annual radial increment of pines after the decrease of plants' emissions.

Scientific novelty of the study. First time in Lithuania a comprehensive dendrochronological research on the impact of climatic factors and industrial pollution on the radial increment of Scots pine (*Pinus sylvestris* L.) has been carried out in the surroundings of "Akmenės cementas" plant; impact of cement dust on pine radial growth has been analyzed; anthropogenic changes of radial increment under the impact of "Akmenės cementas" and "Achema" emissions and after the reduction of emissions have been estimated; analysis of annual radial increment recovery due to reduction of industrial pollution has been carried out and the impact of industrial pollution on the relations between radial increment and climatic factors has been analyzed.

Results of the research provide new knowledge for ecology, environmental research and environmental bioindication, they can be used for the estimation of environmental impact and for the studies of ecology, forest research and environmental research.

Approval of the research work. The main research findings were published in 3 publications in reviewed journals and in 5 proceedings of international and national conferences and workshops. The main study results and statements were presented and discussed in Lithuanian and International conferences and workshops.

Volume and structure of the work. The dissertation is written in Lithuanian. It consists of Introduction, Literature review, Materials and Methods, Results and Discussion, Conclusions and References. The dissertation comprises of 107 pages, including 8 tables, 37 figures and 311 references.

MATERIALS AND METHODS

Scots pine stands in the surroundings of the cement plant "Akmenės cementas" and the nitrogen fertilizer plant "Achema" 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. The reason of choosing the pollution impact zones near these two plants is that these plants are among the largest local pollution sources in Lithuania, and there is an essential difference between the impact of their pollutants.

Study sites characteristics

Pine stands growing in the impact zone of "Akmenės cementas" and "Achema" suffer the long-term anthropogenic impact and this causes the changes in the productivity of trees.

Characteristic of "Akmenės cementas" and its impact zone

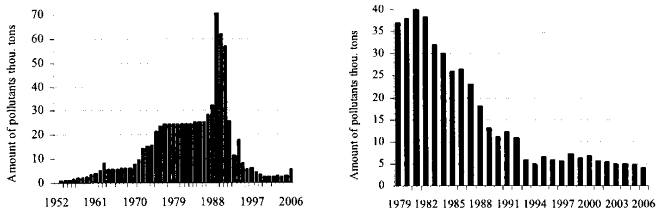
"Akmenės cementas" is situated in the northern part of Lithuania. It is the largest company in the Baltics and the only in Lithuania, producing cement. It began operating in 1952. In the beginning of the 1970s the plant emitted 27 thou. tons of SO_2, 9-10 thou. tons of cement dust, 8.5 thou. tons of NO_x and 1 thou. tons of ashes and other solid particles into the atmosphere annually (Armolaitis at al., 1999b) (Fig. 1, a). 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.

"Akmenės cementas" plant is surrounded by the forests of Naujosios Akmenės forestry of Mažeikiai forest enterprise. Investigation of peat-bog soils at different distances from the plant has revealed the increased amounts of Ca^{2+} (0.5-23.8 cmol/kg) and Mg^{2+} (0.5-2.5 cmol/kg) in the forest floor and the topsoil at distances up to 7-8 km from the plant. That causes alkalization of the topsoil and forest floor (Armolaitis et al., 1999b).

In the period of 1900-1996 yearly investigations of pine stands' defolation and dechromation were carried out in the impact zone of "Akmenės cementas" plant. Significant changes were observed in the nearest vicinity of the plant.

Characteristic of "Achema" and its impact zone

"Achema" plant is situated in the central Lithuania. It began operating in 1965 and it is the largest nitrogen fertilizer producer in the Baltics. The main components of the pollutants are CO, SO_2, NO_2, NH_3 and mineral dust (Stravinskienė, 2002). The largest amount of pollutants was observed in 1979-1982, when 34-40 thou. tons of pollutants were emitted into the atmosphere annually (Armolaitis et al., 1999a) (Fig. 1, b). The emissions decreased to 5-7 thou. tons in recent years.



a b

Fig. 1. Total annual emissions of "Akmenės cementas" (a) and "Achema" (b) plants

"Achema" plant is surrounded by the forests of Jonavos forest enterprise. The most part of soils in the impact zone of the plant are mineral. The surroundings of the plant have been under the impact of air pollution since 1980 when total annual deposition of sulphur comprised about 50 kg/ha at the distance of 1-2 km and over 30 kg/ha at the distance of 20-22 km. Recently it has decreased to 15 kg/ha and 9 kg/ha respectively. Acid depositions from the plant cause the acidification of the surrounding forest soils. This process was determined at the distances of 4-8 km from the plant (Armolaitis et al., 1999a).

Air pollution is considered to be the main cause of a massive forest dieback that peaked in the beginning of the 1980s. Pine stands in the vicinity of the plant in the direction of prevailing winds were damaged most severely (Барткявичюс, 1987). Later the amount of emissions decreased but the area of damaged stands kept spreading and reached the distance of 20-25 km from the plant. The condition of damaged trees stabilized and even began improving since 1990-1991.

Methods and extent of the research

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 (Stravinskienė, 1994).

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.

Extent of the research and characteristics of pine stands

Research has been performed in 65-80-year-old pine stands at different distances (up to 5 km, 5-10 km and further than 10 km) from the "Akmenės cementas" and "Achema" plants in the direction of prevailing winds (north-eastern and eastern). Extent of the research – 20 sample plots (one of them is control) at different distances from "Akmenės cementas" plant and 15 sample plots (two of them are control) in the surroundings of "Achema" plant (Fig. 2). The total number of trees used in the research is 950.

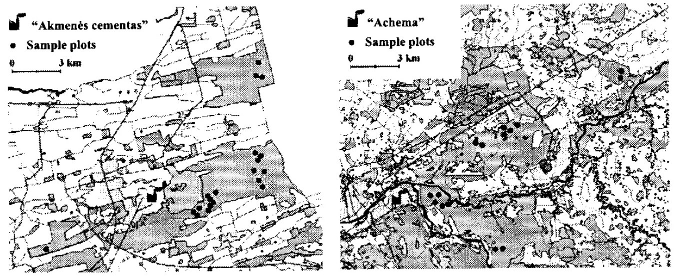


Fig. 2. Distribution of sample plots in the surroundings of "Akmenės cementas" and "Achema" plants

Scots pines in *Carico-sphagno-Pinetum* forest type with identic dendrometric indices were chosen in the surroundings of "Akmenės cementas" plant for the research (Table 1). Non-fertile and acidic (pH 3.5) peat-bog soils dominate in the investigated sites (Pb forest site type).

Table 1. Dendrometric characteristics of the investigated pine stands growing in the impact zone of "Akmenės cementas" plant (P – pine, B – birch, S – spruce)

No.	Stand age, years	Varietal composition	Stocking level	Mean height, m	Mean diameter, cm	Distance from the plant, km	Direction from the plant
1	75	10P	0.7	18	20	2.4	East
2	65	10P	0.7	19	20	2.4	East
3	75	10P	0.8	22	28	3.0	East
4	70	8P2B	0.8	23	30	3.3	East
5	65	10P	0.9	21	22	3.3	East
6	70	10P	0.8	21	24	3.6	East
7	65	6P4B	0.6	24	28	3.8	East
8	65	6P4B	0.6	28	28	3.5	East
9	65	8P2B	0.7	23	26	3.6	East
10	65	10P+B	0.7	23	26	5.9	East
11	70	10P+B	0.7	22	26	6.0	East
12	80	8P2B	0.6	23	26	6.2	East
13	80	8P1S+B	0.7	23	26	6.8	East
14	65	10P+S,B	0.8	22	24	6.8	East
15	80	10P+S	0.8	22	24	7.0	East
16	80	10P+S,B	0.7	23	28	7.1	East
17	80	10P+B	0.6	21	28	13.0	North-east
18	65	7P3S	0.8	26	28	13.5	North-east
19	65	10P	0.7	20	24	14.9	North-east
20	70	8P2B	0.7	25	28	12.0	South-west

Scots pines in *Vaccinio-myrtillo-Pinetum* forest type with identic dendrometric indices were chosen in the surroundings of "Achema" plant for the research (Table 2). Mineral soils dominate in the investigated sites (Nb forest site type).

Table 2. Dendrometric characteristics of the investigated pine stands growing in the impact zone of "Achema" plant (P – pine, B – birch, S – spruce)

No.	Stand age, years	Varietal composition	Stocking level	Mean height, m	Mean diameter, cm	Distance from the plant, km	Direction from the plant
1	75	10P	0.7	23	28	3.3	East
2	72	10P+S	0.7	27	30	3.6	East
3	76	10P	0.7	23	24	3.8	East
4	75	8P1B1S	0.7	28	32	4.3	East
5	70	9P1B	0.7	25	30	4.5	East
6	70	10P+S,B	0.8	22	26	6.9	North-east
7	65	8P2B	0.7	25	24	7.0	North-east
8	80	8P1B1S	0.7	25	28	9.1	North-east
9	70	9P1B	0.6	22	26	10.3	North-east
10	75	9P1S,B	0.7	27	32	10.9	North-east
11	65	10P	0.7	24	26	11.1	North-east
12	75	10P+S	0.7	23	26	19.8	North-east
13	75	10P	0.7	25	30	20.1	North-east
14	80	8P2B,S	0.7	25	30	10.0	South-east
15	80	9P1S	0.7	27	30	9.8	South-east

Data analysis

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) (Holmes, 1994). Tree ring series or their parts with asynchronous growth were eliminated from the next stages of analysis.

Indexation of annual radial increment series

The width of tree rings depends not only on climate but also on other environmental factors: fires, diseases, stand density, tree crown and its changes, tree competition in the stand (Phipps, 1982; Bräker, 1992). 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). Radial increment data standardisation was carried out in order to eliminate the tree age influence on radial increment and to reveal the increment dynamics depending on climate variation. Indices were calculated showing the relation of radial increment of a certain year and the norm of that year's increment. Indexing was carried out in two stages (Holmes, 1994). By using a negative exponential curve and linear regression and after applying the spline function the age curve was removed. The program CHRONOL from the ITRDB Program Library compiled in the University of Arizona by R. L. Holmes was used.

Statistical data analysis

"Statistica" and "Microsoft Excel" software were used for data analysis. The chronologies of radial increment from the stands at different distances from the plants were statistically compared by ANOVA (Fisher criterion F). Differences were considered statistically significant at $p<0.05$ and $F>F_{cr}$.

In the cases of significant effects the differences between each pair of chronologies were investigated by pairwise t-test for independent samples. x was considered statistically significantly less than y at $p<0.05$ and $t<-t_{cr}$ (Student's criterion).

Cluster analysis was used for the estimation of similarity of radial increment series from stands at different distances from the source of pollution. The aim of this analysis is to group the investigated objects to several groups (clusters) so that distances between objects inside the cluster are the smallest and distances between clusters – the largest (Venclovienė, 2000; Čekanavičius, Murauskas, 2002).

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

RESULTS

Impact of climatic factors on the annual radial increment of Scots pine (*Pinus sylvestris* L.)

Variation of climate conditions in Naujoji Akmenė region in 1925-2005

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). It was found that under Lithuanian conditions most important for the formation of tree rings are temperatures of late winter (February), early spring (March, April) and late summer (August), in some cases – temperature of last year's autumn (September, October) (Stravinskienė, 2002; Juknys et al., 2002). Although some authors haven't determined statistically significant relations between radial increment and precipitation, but it was found that pine growth is influenced by precipitation of last year's August and October, as well as current year's early spring and summer (June, July) (Pärn, 2003; Juknys, 2004).

Analysis of the main climatic factors (air temperature and precipitation) of different periods of the year was carried out in Naujoji Akmenė region in order to determine the impact of climatic factors on the radial increment of Scots pine. Šiauliai meteorological station data were used for the analysis of the dynamics of mean air temperature and amount of precipitation of winter months (December-February), the beginning of vegetation (April-May), active vegetation period (May-August) and summer months (June-August).

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

Control stand with analogic 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 (Kairiūkštis, 1990; Armolaitis et al., 1999a; Linderholm, 2001; Juknys et al., 2002; Stravinskienė, 2002; Pederson et al., 2004; Augustaitis, 2005), last year's climate conditions also have influence on tree growth and formation of radial increment. Therefore long-term 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.

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. 3). 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).

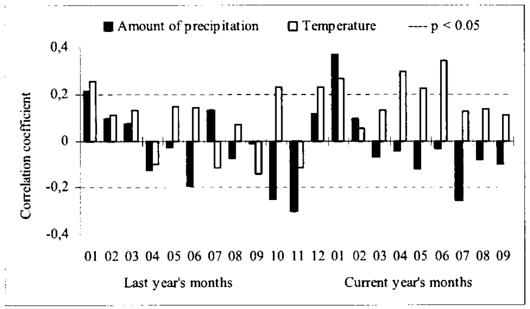


Fig. 3. Pearson correlations between annual radial increment of control pine stands and climatic factors

Results suggest that air temperature and precipitation of the period of active vegetation are important for 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 microbogging processes, which cause significant decrease of radial increment. Similar tendencies were found in the works of other authors (Kairiūkštis, 1994; Stravinskienė, 1997; 2002).

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 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 equals to -0.25 and -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 (Juknys, Vencloviene, 1998; Stravinskienė, 2002) showing strong influence of last autumn's climate conditions.

Scots pine (*Pinus sylvestris* L.) annual radial increment changes due to local pollution of "Akmenės cementas" plant

Anatomical structure of trees allows to evaluate tree growth rate retrospectively from the width of tree rings. Therefore tree ring analysis is one of the most promising and informative methods of estimation of anthropogenic loads and environmental pollution impact on forest ecosystems (Cook, 1987; Juknys, 1994; Schweingruber, 1996; Armolaitis et al., 1999a; Juknys et al., 2002).

There are relatively few investigations carried out on the impact of alkalizing pollutants on ecosystems. Conifer ecosystems with dominating acid mineral soils are considered to be among the most sensitive to the impact of alkaline pollutants (Kaasik et al., 2003). The main purpose of the investigation carried out in the impact zone of "Akmenės cementas" plant is to analyse the changes of radial increment in relatively differently damaged stands, determine the main factors causing radial increment changes and estimate the recovery possibilities of damaged pine stands of *Vaccinio-myrtillo-Pinetum* forest type after the reduction of emissions of alkaline pollutants.

Dynamics of annual radial increment of the investigated stands

Radial increment dynamics shows that before the beginning of pollution radial increment variations were similar in all investigated stands (Fig. 4). 1952 is considered the start of pollution, although plant emissions were not high during the following two decades (Fig. 1, a). Due to increasing plant emissions decline of radial increment dependent on the distance from the pollution source is observed from 1970. Negative pollution impact was strengthened by exclusively cold winter in 1987-1988.

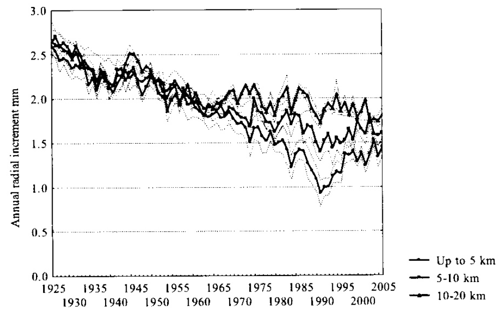


Fig. 4. Dynamics of annual radial increment of the investigated stands

The most significant changes of radial increment were determined in the closest zone (up to 5 km), where pollution is most intensive, and least significant – in the most distant zone (10-20 km). After the reduction of plant emissions increase of radial increment of stands closest to the plant is observed.

Industrial pollution impact on annual radial increment of pines growing at different distances from the plant

In order to estimate possible industrial pollution impact on the radial increment of pines growing near "Akmenės cementas" plant, firstly it was analysed whether differences between increment series 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 $\alpha = 0.05$ (Čekanavičius, 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 radial increment increases with distance from the plant.

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. Relationships between radial increment of pines and emissions were analysed in order to clarify possible reasons for radial increment changes. 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 3). Correlations are weaker between total amount of pollutants and radial increment of pines at the distance of 5-10 km from the plant (r=-0.49; p<0.05) and become statistically insignificant for the most distant pines (p>0.05).

Among the pollution components emissions of SO_2 and solid particles have strongest relations with radial increment of pines closest to the plant (r=-0.65 and r=-0.62 respectively; p<0.05). Slightly weaker correlations were found with emission of NO_x (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 significant, and for the most distant pines correlations became insignificant (p>0.05).

Table 3. Pearson correlations between annual radial increment and emissions during the pollution period and in different stages of pollution intensity (r – Pearson correlation coefficient, p – significance)

	Total emissions	Solid particles	NO_x	SO_2	Total emissions		
	1952-2005				1952-1974	1975-1989	1990-2005
Up to 5 km							
r value	**-0.62**	**-0.62**	**-0.55**	**-0.65**	**-0.89**	**-0.66**	**-0.82**
p value	0.000	0.000	0.000	0.000	0.000	0.007	0.000
5-10 km							
r value	**-0.49**	**-0.49**	**-0.42**	**-0.55**	**-0.65**	**-0.66**	**-0.61**
p value	0.000	0.000	0.002	0.000	0.001	0.008	0.013
10-20 km							
r value	-0.16	-0.15	-0.15	-0.17	-0.31	-0.41	-0.06
p value	0.2	0.2	0.3	0.2	0.16	0.13	0.83

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

In order to detalize possible pollution impact on radial increment, the period of pollution was divided into three stages according to the intensity of plant emissions:

1) the first stage continued from the start of pollution in 1952 till 1974, when annual emissions increased from 5-6 to 16 thou. tons;

2) 1975-1989 – the stage of the largest emissions (24 to 32 thou. tons annually; maximum – 71 thou. tons in 1989);

3) 1990-2005 – the stage of reduction of emissions, which was caused by general industrial decline, modernization of technologies, later – by the effective use of resources. During this stage annual emissions decreased from 25 to 3 thou. tons.

Results have shown that strongest and most significant negative correlations exist between radial increment of stands closest to the plant (up to 5 km) and total emissions in all stages of pollution (r varies from -0.66 to -0.89; p<0.05) (Table 3).

Correlation analysis has confirmed the hypothesis that possible negative pollution impact is different for stands growing at different distances from the plant, and relationships between pollution and radial increment decrease with distance from the pollution source.

Linear one variable regression analysis was carried out in order to determine the relative strength of possible pollution impact during different stages of pollution. Results show different strenght of pollution impact on radial increment of pines at different distances from the plant (Fig. 5). At the beginning of the first stage of pollution radial increment of pines at the distances of up to 5 km and 5-10 km was similar. Due to gradually increasing amount of plant emissions quantitative radial increment differences between these distances became significant (Fig. 5, a).

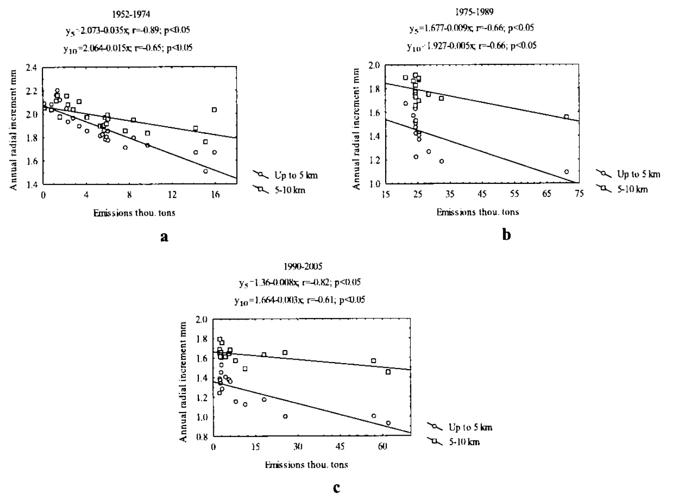


Fig. 5. The relationships between annual radial increment and emissions in different stages of pollution intensity

The impact strength and the rate of radial increment changes are determined by the values of linear regression equation's slope parameter b: the greater the absolute value of b, the stronger the impact and the higher the rate of radial increment change.

Positive b sign indicates that y increases with increasing x, and negative sign means that y decreases with increasing x (Čekanavičius, Murauskas, 2002).

Having compared the values of b for the pine stands growing at the distances of up to 5 km and 5-10 km for the first stage 1952-1974 (-0.035 ($y = 2.073 - 0.035x$) and -0.015 ($y = 2.064 - 0.015x$) respectively), it is seen that pine stands closer to the plant are more effected by the pollution than the stands at 5-10 km distance (Fig. 5, a). Negative sign of b means that radial increment decreases with increasing emissions. In 1975-1989 radial increment of pines at the distances of up to 5 km and 5-10 km still reacts to the increasing pollution negatively, but the difference between the slopes of functions has reduced: -0.009 ($y = 1.677 - 0.009x$) and -0.005 ($y = 1.927 - 0.005x$) respectively (Fig. 5, b). This suggests that reaction of pine increment to the amount of pollutants during that stage was similar. Since 1990 plant emissions start reducing (Fig. 1, a) and b values for the stage 1990-2005 are: -0.008 ($y = 1.36 - 0.008x$) and -0.003 ($y = 1.664 - 0.003x$) (Fig. 5, c). Negative sign of b shows that reduction of pollution induces positive changes of radial increment.

Linear regression analysis also confirms the hypothesis that pollution impact is different for stands at different distances from the plant, and the impact decreases with distance. The scatter of data in Fig. 5 suggests that pollution is not the only factor causing the variation of radial increment of investigated stands.

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

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 (Ots, Rauk, 1999; Juknys et al., 2003; Thompson, 2003; Augustaitis, 2005).

Firstly multiple regression models based only on pollution components were constructed. The form of function used for the formation of the models is:

$$y = a + b_1x_1 + b_2x_2 + ... + b_kx_k, \quad (1)$$

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

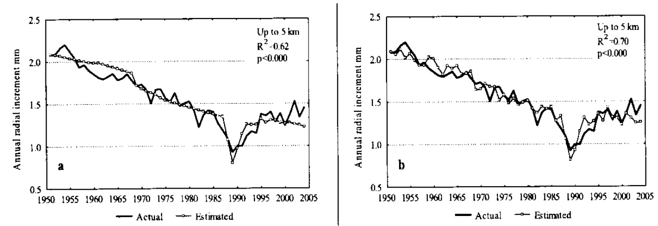
Non-standardized b coefficients do not allow the intercomparison of the variables and determination of their relative relevance when calculating y values, because the magnitude of b depends on the dimension of x_i and the scatter of data. Relative influence of independent variables (pollution components) 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, Murauskas, 2002).

Regression model including the main components of "Akmenės cementas" plant emissions – solid particles, NO_x and SO_2, explains 62 % of radial increment variation (R^2=0.62) (Fig. 6, a). β coefficients 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).

The dependence of tree increment on emissions decreases with increase of distance from the pollution source (R^2=0.36 for the distance of 5-10 km) and for the stands at 10-20 km from the plant it 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.

Having compared the radial increment series of the stands closest to the plant it is seen that approximation of increment variation improved (R^2=0.70) (Fig. 6, b). 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).



a:

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

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)

b:

$$P_t = (-3.45 + 5.99*\exp(-0.003*t))\,(67.08 + 1.98TAug_{t-1} - 0.97TNov_{t-1} - 0.06PJul_t - 2.39KD_{10} + 4.2NO_x - 2.63SO_2)$$

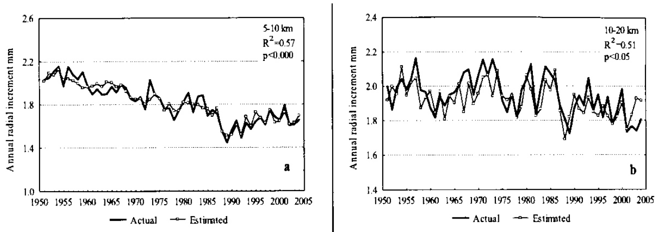
β ($TAug_{t-1}$)=0.24 (p=0.01)
β ($TNov_{t-1}$)=-0.18 (p=0.04)
β ($PJul_t$)=-0.19 (p=0.03)
β (KD_{10})=-0.75 (p=0.002)
β (NO_x)=0.57 (p=0.001)
β (SO_2)=-0.47 (p=0.02)

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

Fig. 6. Dynamics of actual and estimated annual radial increment of stands growing up to 5 km from the plant during the pollution period (1952-2005)

Approximation level R^2 decreases with distance from the pollution source. At the distance of 5-10 km from the plant the influence of solid particles becomes insignificant and the emissions of SO_2 become more relevant (Fig. 7, a). Influence of last November's temperature gets stronger (β=-0.28; p=0.01), and new significant factors emerge – temperatures of last October and current year's September as well as precipitation of current year's August. Model describes 57 % of radial increment variation (R^2=0.57).

Only climatic factors remain in regression model for the radial increment of the most distant stands (Fig. 7, b). Model reveals the importance of climatic conditions of last year's autumn. Influence of last October's temperature and precipitation as well as influence of last November's temperature are significant. 51 % of radial increment variation is explained by the regression model (R^2=0.51).



$$P_t = (1.41 + 1.29*\exp(-0.02*t))\ (86.82 + 0.81TOct_{t-1} - 0.66TNov_{t-1} - 0.02PAug_t + 0.79TSep_t + 2.06NO_x - 2.3SO_2)$$

Standardized coefficients:
$\beta\ (TOct_{t-1})=0.24\ (p=0.02)$
$\beta\ (TNov_{t-1})=-0.28\ (p=0.01)$
$\beta\ (PAug_t)=-0.21\ (p=0.04)$
$\beta\ (TSep_t)=0.23\ (p=0.02)$
$\beta\ (NO_x)=0.66\ (p=0.000)$
$\beta\ (SO_2)=-0.97\ (p=0.000)$

$$P_t = (1.79 + 0.82*\exp(-0.03*t))\ (123.77 - 0.05POct_{t-1} + 0.83TOct_{t-1} - 0.81TNov_{t-1} + 0.8TMay_t + 0.42TSep_t)$$

$\beta\ (POct_{t-1})=-0.39\ (p=0.001)$
$\beta\ (TOct_{t-1})=0.23\ (p=0.03)$
$\beta\ (TNov_{t-1})=-0.42\ (p=0.001)$
$\beta\ (TMay_t)=0.31\ (p=0.01)$
$\beta\ (TSep_t)=0.29\ (p=0.01)$

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

Fig. 7. Dynamics of actual and estimated annual radial increment of stands at the distances of 5-10 km (a) and 10-20 km (b) from the plant during the pollution period (1952-2005)

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. Several factors, such as temperature of last October, November and current year's September are included in more than one model. This shows radial increment dependence on certain climatic factors, typical for that habitat.

Not only the intensity of growth, but also the relations between tree growth and different climatic factors can be transformed in the polluted environment. For the estimation of changes in relations between radial increment of pine stands and climate, increment series were split into two parts (till 1952 and from 1952) and their relations were analysed separately. Increment of the closest pine stands was analysed so that possible changes in relations are more pronounced.

Pearson correlation analysis has shown that in most cases radial increment relations with mean temperature of different months are stronger in the pollution period than in the period till 1952 (Fig. 8), and correlations with precipitation become weaker.

It is seen from Fig. 8 that in the polluted environment radial increment relations with temperatures of January, February, March and April as well as with precipitation of March and August increased most considerably. Correlations with temperature of last year's September and both years' June as well as with precipitation of May, June and last year's October have decreased.

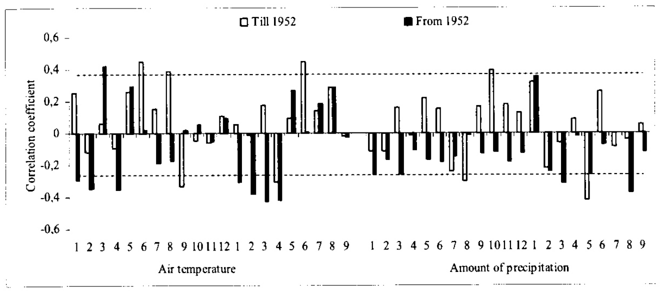


Fig. 8. Comparison of relations between annual radial increment of damaged trees and climatic factors before the pollution and in the pollution period (--- significance level ($p<0.05$))

Results have shown that industrial pollution transforms radial increment relations with climatic factors. In the impact zone of "Akmenės cementas" pines become more sensitive to temperature, and sensitivity to precipitation decreases.

Estimation of anthropogenic radial increment changes

One of the aims of multiple regression is the prediction of dependent variable (annual radial increment in this case). For the estimation of anthropogenic radial increment changes tree ring series were divided into two periods: 1925-1969 and 1970-2005. Although "Akmenės cementas" plant began its operation in 1952, emissions were low till 1969 (up to 6 thou. tons) and differences of radial increment of the surrounding pine stands were not significant (Fig. 4). Multiple climate response models were constructed according to the first part (calibration) of the series (Table 4) in order to evaluate how the tree would have grown if environment had not been polluted. Radial increment series were standardized for the elimination of age influence.

Table 4. Climate response models for annual radial increment of pine stands growing at different distances from the plant

Distance from the plant	Model
Up to 5 km	$P_t = (-3.45 + 5.99*\exp(-0.003*t))\ (90.27 + 0.14PJan_{t-1} + 0.35TDec_{t-1} - 0.1PFeb_t - 0.06PMay_t - 0.03PJul_t + 1.35TSep_t)$; $R^2=0.41$; $p<0.002$
5-10 km	$P_t = (1.41 + 1.29*\exp(-0.02*t))\ (106.49 - 0.08PJan_{t-1} + 0.06PSep_{t-1} - 0.32TFeb_{t-1} + 0.34TMar_{t-1} + 0.15PApr_t - 0.04PJul_t + 1.41TSep_t)$; $R^2=0.46$; $p<0.001$

Where: P_t – tree-ring width (mm); t – tree age (years); P – month's amount of precipitation (mm); T – month's mean temperature (°C); R^2 – determination coefficient; p – significance.

The predicted radial increment norm was calculated for the second period (1970-2005) and according to the differences between the actual values and these estimated by the model the effect of environmental pollution on tree growth has been assessed. Models were constructed only for pines at the distance of up to 5 km and 5-10 km, because according to the results of previous analysis no significant relations were found between plant emissions and radial increment of the most distant pine stands.

In these models some climatic factors dominate, because radial increment variation before the pollution is similar for all the investigated stands. For the closest stands precipitation of last January (β=0.38) and temperature of current year's September (β=0.4) have the strongest influence compared to other factors in the model. Model describes 41 % of radial increment variation (R^2=0.41).

The most important factors for the stands at 5-10 km are precipitation of last August and current year's April as well as temperature of current year's September (β equals to 0.41, 0.59 and 0.47 respectively; p<0.05). Model describes 46 % of radial increment variation (R^2=0.46).

Comparison of actual and estimated radial increment values is given in Fig. 9. As it is seen, significant decrease of radial increment of the closest pine stands (up to 5 km) compared to the predicted norm is observed from 1981 (Fig. 9, a). It could be explained by a considerable increase of plant emissions and their negative impact on the stands. An exclusively cold winter in 1979-1980 was an additional unfavourable factor.

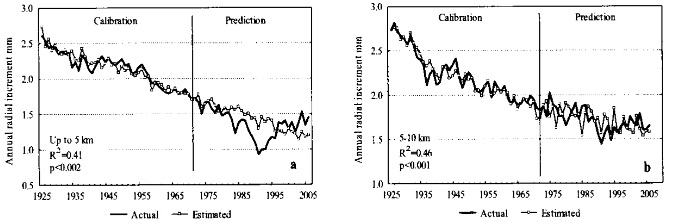


Fig. 9. Comparison of actual and predicted annual radial increment series of stands growing up to 5 km (a) and at the distance of 5-10 km (b) from the plant

The most significant drop of radial increment in 1990 was caused by the maximum plant emissions that year (71 thou. tons). Since 1990 due to considerable reduction of plant emissions increase of radial increment is observed. Pine growth depression period lasted about 11 years, and radial increment was on average 15 % lower than the predicted norm. Difference between actual and estimated series during this period was statistically siginificant (Student's criterion $|t|$=3.71 (p<0.05) > t_{kr}=1.74). Around 1995 actual radial increment reached the predicted norm, and during the last years fluctuated above it.

For the pines at the distance of 5-10 km from the plant the depression period was not so clearly expressed: it began in 1989 and lasted about 5 years (Fig. 9, b). Radial increment was about 7 % lower than the predicted norm, and the difference is statistically significant (Student's criterion $|t|$=2.4 (p<0.05) >t_{kr}=1.9). Since 1995 radial increment fluctuated around the estimated values and in last few years exceeded it.

Recovery of the damaged pine stands after the reduction of emissions of alkalizing pollutants

Since 1990 the amount of "Akmenės cementas" plant annual emissions decreased significantly (Fig. 1), which gave the opportunity to observe the recovery process of damaged forest ecosystems. Period from 1990 to 2005 was taken for the analysis of radial increment recovery and was divided into three stages:

1) 1990-1994 – stage of abrupt reduction of annual emissions (from 62 thou. tons in 1990 to 18 thou. tons in 1994);
2) 1995-2000 – stage of gradual decrease of annual emissions from 8 to 3 thou. tons;
3) 2001-2005 – stage of stabilization of amount of annual emissions around 2.8 thou. tons.

Radial increment averages were calculated for the selected stages and quantitative changes of radial increment were estimated (Fig. 10). The period of 1985-1989 was taken additionally for the comparison and evaluation of increment changes and the rate of recovery.

In 1990-1994, after the abrupt reduction of emissions, decrease of radial increment of pines closest to the plant (up to 5 km) is observed. This could be explained by the strong impact of pollution maximum in 1989. The average of radial increment of this stage was 18 % less than that of the 1985-1989 period (the decrease is statistically significant) and comprised 45 % of radial increment average before the start of pollution.

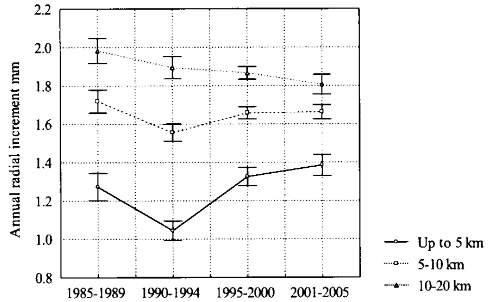


Fig. 10. Dynamics of annual radial increment means of damaged trees in 1985-2005

In 1995-2000, due to subsequent gradual decrease of plant emissions, radial increment recovery was determined. The average of radial increment of this stage increased statistically significantly by 28 % compared to the past stage (1990-1994). In 2001-2005, when plant emissions had stabilized, positive effect of pollution reduction remained: radial increment increased by additional 5 % compared to the 1995-2000 stage, but this increase was statistically insignificant. Hence at the end of the investigated recovery period radial increment of pines closest to the plant had recovered by 33 % on average compared to the decline in 1990-1994.

Radial increment of pines at 5-10 km from the plant decreased in 1990-1994 after intensive pollution in 1989 and comprised 66 % of the level before the start of pollution. In 1995-2000 gradual reduction of plant emissions caused the increase of pine radial increment by 6 % compared to the past stage (1990-1994), but the increase was statistically insignificant. In the last stage, when plant emissions stabilized to minimal level, no increase of radial increment was determined.

According to the results of previous analysis, no relation was established between plant emissions and radial increment of pines most distant from the plant (10-20 km), therefore no recovery processes were recorded in the period of pollution reduction.

Dendroecological investigations of Scots pine (*Pinus sylvestris* L.) under the impact of "Achema" plant pollution

First signs of forest damages due to anthropogenic pollution first of all revealed near the "Achema" plant. Therefore most comprehensive data on the changes of forest ecosystem condition were collected there and most investigations on the growth of Scots pine stands under the impact of plant's pollution were performed (Armolaitis et al., 1999a; Juknys et al., 2002; Stravinskienė, 2002; Juknys et al., 2003; Stravinskienė, 2004). The main purpose of this investigation in the impact zone of "Achema" plant is to analyse the changes of pine radial increment in stands affected by different amount of pollutants, to investigate the recovery possibilities of pine stands of *Vaccinio-myrtillosa* forest type after the reduction of emissions of acidifying and eutrophying pollutants.

Variation of climate conditions in Jonava region in 1920-2005

Variation of the main climatic factors (air temperature and amount of precipitation) in Jonava region was analysed in order to determine the impact of climatic factors on the radial increment. Kaunas meteorological station data were used for the analysis of the dynamics of mean air temperature and amount of precipitation of winter months (December-February), the beginning of vegetation (April-May), active vegetation period (May-August) and summer months (June-August).

Dynamics of annual radial increment of the investigated stands

Dynamics of radial increment series shows similar variation trends (Fig. 11). Before the plant construction the periods of increment decrease are related to winter colds, low temperatures of the beginning of vegetation, precipitation lower than long-term average and cool periods of active vegetation. After 1965, in the first decade of pollution, the variation of radial increment of all investigated pine stands was periodic, and the increase of radial increment was observed.

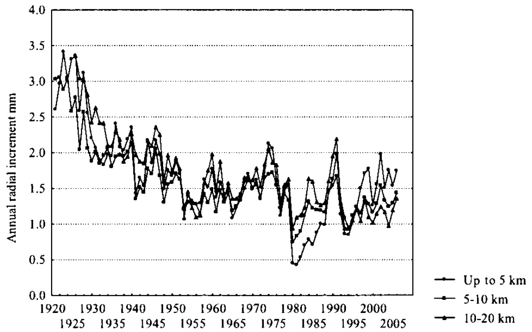


Fig. 11. Dynamics of annual radial increment of the investigated stands

A decrease of annual radial increment can be observed since 1975-1976 because of negative impact of pollutants. The exclusively cold winter of 1979-1980 was an additional external factor causing a very rapid decrease of radial increment that year. It

should be noted that after the start of the most polluting Nitrophosca department in 1978 annual emissions of "Achema" plant increased and reached the maximum (37 thou. tons) in 1979. The recovery of damaged stands started in 1986-1987 as a consequence of different pollution mitigation measures introduced (Armolaitis et al., 1999a).

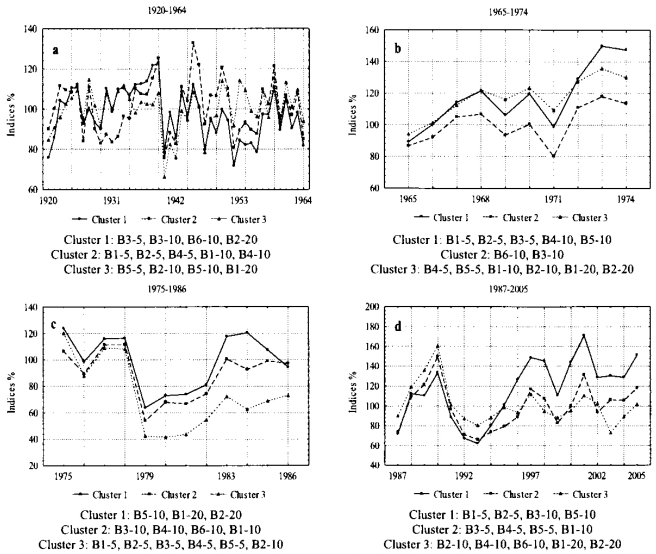
A significant increase of radial increment can be observed after the accident in the Nitrophosca department and its closure in 1989, which caused the reduction of plant emissions. In 1992-1994 radial increment decreased due to unfavourable climate conditions (exclusively dry summers in 1992 and 1994). During the last decade most intensive recovery of growth rate can be observed in the pine stands closest to the plant.

Dynamics of radial increment of the investigated stands shows that variations of increment series are similar despite relatively large distances between the stands, and differences between series' averages are small. Cluster analysis was performed for more accurate description of radial increment variation regularities and their reasons. Series of radial increment indices were divided into 3 groups (clusters) by the non-hierachical "*k*-means" method according to variation similarities so that differences inside the groups are the least and differences between the groups are the largest. The number of clusters was chosen considering the increment data distribution according to the distance from the pollution source. The expected result was as more series of the same distance as possible in each cluster. That would allow to evaluate environmental impact on pine stands situated at different distances from the plant. In order to get more information about radial increment variation dependence on the changing environmental factors, the whole investigation period was divided into 4 periods: period before the start of pollution (1920-1964), period of temporary radial increment increase (1965-1974), depression period (1975-1986) and recovery period (1987-2005).

Results of cluster analysis show different composition of clusters in different periods (Fig. 12). In the period before the start of pollution (1920-1964) each cluster contains increment series from different distances (Fig. 12, a). This suggests that before the start of pollution variations of radial increment series of stands at all distances were similar because they were caused only by natural factors.

In the second period (1965-1974) signs of series' differentiation according to the distances can be noticed (Fig. 12, b). Most increment series in the first cluster are from the closest vicinity of the plant (up to 5 km) and second cluster contains increment series of pines at 5-10 km from the plant. This suggests that an external factor has appeared causing radial increment differences between the groups. Also during this period temporary increase of radial increment in all clusters can be observed which was caused by the positive impact of emitted nitrogen compounds (Armolaitis et al., 1999a; Juknys et al., 2002).

Since 1975 pollution impact became negative and that caused a decrease of radial increment of stands at different distances from the plant (Fig. 12, c). First cluster comprises stands most distant from the plant (10-20 km). The drop of radial increment was the least compared to other clusters, but considerable. The most considerable decrease of radial increment is observed in the series of the third cluster which comprises stands closest to the pollution source. Hence the pollution impact gradient is most clearly revealed during this period.



Where: B1-B6 – sample plot number; 5,10 ir 20 – sample plot distance from the source of pollution

Fig. 12. Dynamics of the means of clusters containing the most similar series of annual radial increment indices

In the period of pollution reduction to the constant minimum level and radial increment recovery (1987-2005) clusters contain various series from different distances from the plant (Fig. 12, d). Such mixed distribution of radial increment series in the clusters suggests that differences between pine growth at different distances from the plant have decreased significantly.

Complex impact of climatic factors and industrial pollution on the formation of pine annual radial increment

Climatic factors impact on annual radial increment. Relatively undamaged control stand situated 10 km south-east from the plant was selected for the determination of relations between climatic factors and radial increment. Long-term meteorological data (month's mean temperature and amount of precipitation) of last year's January-December and current year's January-September were used for the analysis.

The strongest and statistically significant correlations were found between radial increment and temperature of late winter as well as early spring (Fig. 13). Strongest positive increment relations were determined with temperatures of January (r=0.31; p<0.05), February (r=0.40; p<0.05), March (r=0.39; p<0.05) and April (r=0.26; p<0.05).

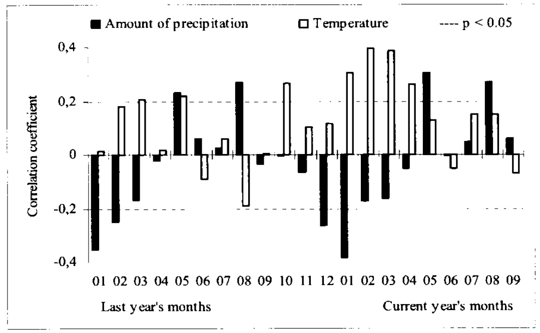


Fig. 13. Pearson correlations between annual radial increment of control pine stands and climatic factors

Radial increment relations with precipitation are weaker than those with temperature, but negative increment correlations with precipitation of January (r=-0.38; p<0.05) and positive correlations with precipitation of May (r=0.30; p<0.05) and August (r=0.27; p<0.05) are statistically significant.

Last year's climate conditions are also important to the formation of radial increment: correlations with precipitation of January (r=-0.35; p<0.05) and December (r=-0.26; p<0.05) are negative. Positive relations were found with temperature of last March, May and October (r equals to 0.21, 0.22 and 0.27 respectively; p<0.05).

Impact of industrial pollution on annual radial increment. In order to clarify possible reasons for changes of pine radial increment at different distances from the pollution source, correlative relationships were analysed between radial increment and amount of pollutants. The strongest and statistically significant negative correlations were found between plant emissions and radial increment of pines closest to the plant (r=-0.81; p<0.05) (Table 5).

Table 5. Pearson correlations between annual radial increment and total emissions and their components (r – Pearson correlation coefficient, p – significance)

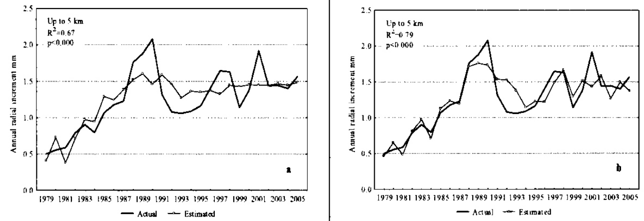
	Total emissions	NO_x	SO_2	Dust
Up to 5 km				
r value	**-0.81**	**-0.77**	**-0.81**	**-0.78**
p value	0.000	0.000	0.000	0.000
5-10 km				
r value	**-0.47**	**-0.41**	**-0.47**	**-0.58**
p value	0.01	0.03	0.01	0.001
10-20 km				
r value	-0.38	-0.32	-0.36	**-0.51**
p value	0.05	0.1	0.06	0.006

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

Further from the plant relations get weaker, but remain statistically significant (r=-0.47; p<0.05). Correlation between radial increment of most distant pine stands and plant emissions becomes statistically insignificant (p=0.05).

Results have shown that relations between radial increment and pollution components (NO_x, SO_2 and mineral dust) are different for different distances from the plant. Multiple regression analysis on dependence of annual radial increment on the amount of emissions of different pollutants has been performed while investigating the impact of air pollution on tree growth. Actual and estimated values of radial increment of pines closest to the plant (up to 5 km) for the period of 1979-2005 are presented in Fig. 14. As it is seen, the regression model including mineral dust as well as nitrogen and sulphur oxides as the main factors describes 67 % of radial increment variation (R^2=0.67) (Fig. 14, a). Relative influence of all components is similar, but influence of SO_2 (β=-0.99; p=0.02) and mineral dust (β=-0.82; p=0.01) is negative and influence of NO_x is positive (β=1.04; p=0.01).

Complex impact of climatic factors and industrial pollution on annual radial increment. Since changes of tree increment depend not only on air pollution, but on climatic factors as well, in order to approximate radial increment variation more exactly, values of climatic factors (month's mean temperature and amount of precipitation) were included into multiple regression model additionally. Climatic factors significantly correlating with radial increment were used in the model. It is seen that approximation of radial increment variation gets much better (R^2=0.79) (Fig. 14, b). After the inclusion of climatic factors into the model, relative influence of pollutants slightly reduced and remained stronger than that of climatic factors. NO_x has the strongest and positive influence (β=0.96; p=0.01). The influence of precipitation of last year's January and temperature of current year's February is much weaker but statistically significant (p<0.05).



a: $P_t = (1.27 + 1.99*\exp(-0.06*t))\ (102.91 - 5.57D + 22.99NO_x - 18.81SO_2)$

b: $P_t = (1.27 + 1.99*\exp(-0.06*t))\ (124.97 - 0.44PJan_{t-1} + 1.54TFeb_t - 5.68D + 21.23NO_x - 14.54SO_2)$

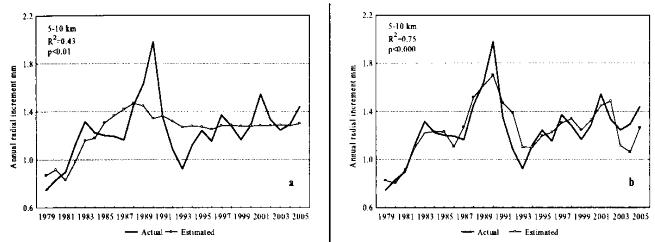
Standardized coefficients:

	a	b
Standardized coefficients:	β (D)=-0.82 (p=0.01)	β ($PJan_{t-1}$)=-0.26 (p=0.02)
	β (NO_x)=1.04 (p=0.01)	β ($TFeb_t$)=0.19 (p=0.01)
	β (SO_2)=-0.99 (p=0.02)	β (D)=-0.84 (p=0.003)
		β (NO_x)=0.96 (p=0.01)
		β (SO_2)=-0.76 (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 temperature (°C); D – amount of dust (thou. t); NO_x – amount of nitrogen oxides (thou. t); SO_2 – amount of sulphur dioxide (thou. t).

Fig. 14. Dynamics of actual and estimated annual radial increment of stands growing up to 5 km from the plant in 1979-2005

Approximation level R^2 decreases with increasing distance from the pollution source (Fig. 15). Regression model based on pollution components describes 43 % of the changes of radial increment of pines situated at 5-10 km distance from the plant and reveals stronger influence of mineral dust and weaker influence of NO_x compared to the model for the closest pine stands (Fig. 15, a). After the inclusion of climatic factors into the model relative influence of mineral dust and NO_x remains the strongest (Fig. 15, b). Positive influence of the temperature of last year's February and October on radial increment appears. Influence of the temperature of current year's February is stronger than that for the closest pine stands. Regression model describes 75 % of radial increment variation (R^2=0.75).



a: $P_t = (1.3 + 1.8*\exp(-0.08*t))\ (96.03 - 4.76D + 8.53NO_x)$

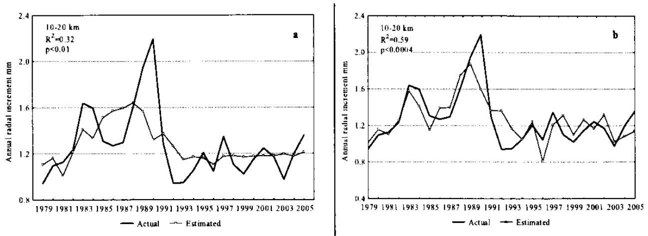
b: $P_t = (1.3 + 1.8*\exp(-0.08*t))\ (69.44 + 1.46TFeb_{t-1} + 4.44TOct_{t-1} + 2.27TFeb_t - 4.68D + 13.14NO_x)$

	a	b
Standardized cofficients:	β (D)=-1.17 (p=0.003)	β ($TFeb_{t-1}$)=0.31 (p=0.03)
	β (NO_x)=0.64 (p=0.009)	β ($TOct_{t-1}$)=0.34 (p=0.007)
		β ($TFeb_t$)=0.48 (p=0.001)
		β (D)=-1.15 (p=0.000)
		β (NO_x)=0.98 (p=0.002)

Where: P_t – tree ring width (mm); t – tree age (years); T – month's mean temperature (°C); D – amount of dust (thou. t); NO_x – amount of nitrogen oxides (thou. t).

Fig. 15. Dynamics of actual and estimated annual radial increment of stands at the distance of 5-10 km from the plant in 1979-2005

According to the results of multiple regression analysis, even the most distant pine stands suffer the impact of "Achema" plant emissions (Fig. 16), and negative influence of mineral dust as well as positive influence of NO_x remains strong, but model based only on pollution components explains only 32 % of radial increment variation (R^2=0.32) (Fig. 16, a). Approximation of radial increment variation gets better when climatic factors are included additionally (R^2=0.59) (Fig. 16, b). In this model, like at closer distances from the plant, influence of mineral dust and NO_x remains strong and temperature of current year's February dominates, but positive influence of January's temperature appears.



$P_t = (1.29 + 5.17{*}\exp(-0.07{*}t))\ (83.6 - 6.18D + 19.9NO_x)$

$P_t = (1.29 + 5.17{*}\exp(-0.07{*}t))\ (89.59 + 1.36TJan_t + 2.42TFeb_t - 6.23D + 24.29NO_x)$

Standardized coefficients:

a	b
β (D)=-1.29 (p=0.003)	β ($TJan_t$)=0.25 (p=0.04)
β (NO_x)=1.27 (p=0.004)	β ($TFeb_t$)=0.43 (p=0.007)
	β (D)=-1.3 (p=0.000)
	β (NO_x)=1.55 (p=0.001)

Where: P_t – tree ring width (mm); t – tree age (years); T – month's mean temperature (°C); D – amount of dust (thou. t); NO_x – amount of nitrogen oxides (thou. t).

Fig. 16. Dynamics of actual and estimated annual radial increment of stands at the distance of 10-20 km from the plant in 1979-2005

Having compared the results of multiple regression analysis, it is seen that, contrary to the surroundings of "Akmenės cementas" plant, emitted pollutants spread to greater distances from "Achema" plant and their impact remains even on the more distant pine stands.

In order to determine whether "Achema" pollution transforms the relations between pine radial increment and climatic factors, like in the surroundings of "Akmenės cementas", correlation analysis was carried out. Radial increment series of the pine stands closest to the plant was divided into two parts – till 1965 and from 1965. Results have shown that in the polluted environment radial increment dependence on climatic factors in most cases is stronger than before the pollution (Fig. 17).

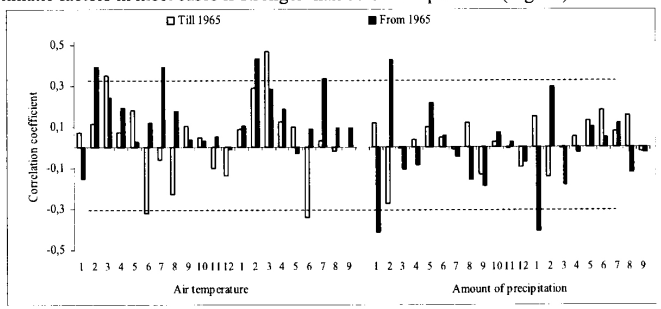


Fig. 17. Comparison of relations between annual radial increment of damaged trees and climatic factors before the pollution and in the pollution period (--- significance level (p<0.05))

Stronger radial increment relations were found with temperature of late winter (February) and summer (July, August) as well as precipitation of winter months (January, February). Correlations with temperature of March and June became weaker. Results obtained confirm that relations between radial increment and climate are transformed by the pollution. Pine stands growing in the surroundings of "Achema" in most cases become more sensitive to precipitation, and sensivity to temperature increases in smaller number of cases.

Anthropogenic changes of annual radial increment under the impact of acidifying and eutrophying pollutants

In order to estimate anthropogenic changes of pine radial increment it is important to evaluate what normal growth of pines would have been if the environment had not been polluted. For this purpose multiple climate response models have been constructed. Tree ring series were divided into two periods – prior to the construction of the plant (1920-1964) and after its construction (1965-2005). Climate response models for the pine stands situated at different distances from the plant have been constructed according to the first (calibration) part of the series and are given in Table 6.

Table 6. Climate response models for annual radial increment of pine stands growing at different distances from the plant

Distance from the plant	Model
Up to 5 km	$P_t = (1.27 + 1.99{*}\exp(-0.06{*}t))\ (90.27 + 0.17PJun_t + 0.07PJul_t + 1.53TFeb_t + 0.99TMar_t)$; R^2=0.53; p<0.000
5-10 km	$P_t = (1.3 + 1.8{*}\exp(-0.08{*}t))\ (101.56 + 0.07PJun_{t-1} + 1.24TFeb_t + 1.21TMar_t$; R^2=0.51; p<0.000
10-20 km	$P_t = (1.29 + 5.17{*}\exp(-0.07{*}t))\ (125.41 - 4.76TSep_{t-1} + 4.91TOct_{t-1} + 2.42TMar_t$; R^2=0.44; 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 temperature (°C); R^2 – determination coefficient; p – significance.

At the closest distance from the plant (up to 5 km) influence of February's temperature is the strongest compared to other factors in the model (β=0.45; p=0.001). Model describes 53 % of radial increment variation (R^2=0.53). Temperature of current year's February remains the most important climatic factor influencing radial increment formation of pines at 5-10 km distance from the "Achema" plant (β=0.46; p<0,05). Model approximation level is 51 % (R^2=0.51). Radial increment of pines at most distant stands (10-20 km) was influenced by the temperature of March (β=0.42; p=0.004) as well as last year's September (β=-0.41; p=0.005) and October (β=0.47; p=0.001). Model resolves 44 % of radial increment variation in these stands (R^2=0.44).

By including the values of selected climatic factors of the second period (1965-2005) it has been predicted how trees would have grown if atmosphere pollution had not started, and the estimated values were compared with the actual ones (Fig. 18).

As seen from the data, since 1965, when "Achema" started producing fertilizers, increase of radial increment can be observed compared to the predicted norm. This increase can be explained by the positive impact of emitted nitrogen compounds, because these pollutants at first act like fertilizers. The duration of this fertilization period was almost the same for all stands irrespective of the distance from the plant (7-8 years). Radial increment of pines closest to the plant (up to 5 km) was on average by 24 %, at the distance of 5-10 km – by 17 % and at the distance of 10-20 km – by 23 %

higher than the normal growth, and the differences between each couple of series are statistically significant (Student's criterion t; $p<0.05$).

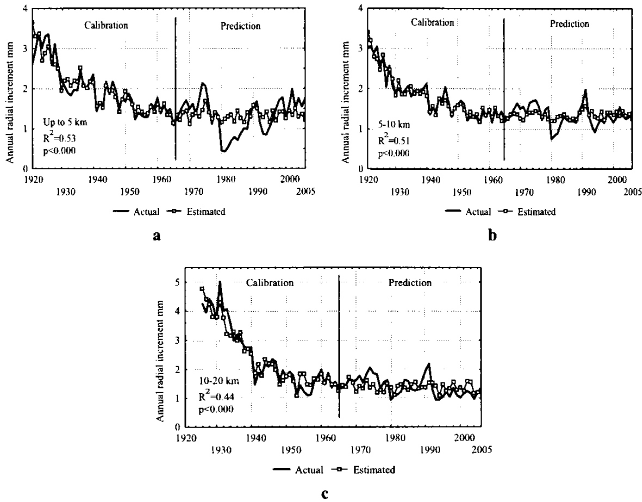


Fig. 18. Comparison of actual and predicted annual radial increment series of the investigated stands

Since 1979 a very rapid decrease of radial increment compared to the normal growth can be observed, which is explained by considerable increase of plant emissions and general negative impact of pollution. The exclusively cold winter of 1979-1980 was an additional unfavourable factor. The most considerable drop of radial increment in 1980 was caused by the maximum amount of plant emissions (37 thou. tons) in 1979. The period of pine growth depression due to intensive pollution lasted 11 years in the stand closest to the plant (Fig. 18, a) and about 6 years in more distant stands. The average losses of radial increment comprised about 38 % for the closest stand. Difference between actual and estimated radial increment averages during the depression period is statistically significant (Student's criterion $|t|=3.73>t_{cr}$, $t_{cr}=1.73$). At the distance of 5-10 km from the plant radial increment was on average 15 % lower than the predicted norm, and difference between increment averages was also statistically significant (Student's criterion $|t|=2.64>t_{cr}$, $t_{cr}=1.81$) (Fig. 18, b). Radial increment losses for the most distant stands comprised 7 %, and difference between increment averages is statistically insignificant (Student's criterion t; $p>0.05$) (Fig. 18, c).

Results suggest that even though the impact of plant pollutants is spread far from the plant, the closest pine stands are damaged most considerably.

Recovery processes in the damaged pine stands after the reduction of plant emissions

Since 1982 reducing amount of "Achema" emissions induced the recovery of damaged pine stands' growth and condition. According to the results of multiple regression analysis, increase of radial increment is observed in all investigated stands (Fig. 18), and the process of recovery is rather different for differently damaged stands. Stands with most depression of tree growth (up to 5 km) have reached normal level of annual increment only at the very end of 1980s. Later due to slightly increased plant emissions in 1991-1992 and unfavourable climate conditions (dry and hot summers in 1992 and 1994 and cool rainy summer in 1993) a temporary deviation from the normal growth can be observed. Since 1995 radial increment recovery takes place and in 1997-2005 it exceeds the estimated norm by 21 % on average. Difference between increment series in this period is statistically significant (Student's criterion $|t|=3.84>t_{cr}$, $t_{cr}=1.75$).

Radial increment of stands situated further from the plant reached normal level in 1983 and exceeded it in 1990. That year radial increment of pines at 5-10 km distance from the plant was 25 % and at the distance of 10-20 km – 44 % higher than the norm predicted by the model (Fig. 18, b, c). This was caused by the favourable climate conditions (warm winter and warmer than long-term average beginning of vegetation in 1989-1990). In 1992-1994 exclusively dry summers caused a significant decrease of radial increment. During last few years radial increment of pines at 5-10 km from the plant reached the predicted level (Fig. 18, b), and pine increment of stands at 10-20 km from the plant fluctuated a little lower than the norm (Fig. 18, c).

In order to estimate relations between reducing pollution and radial increment more exactly, linear one variable regression analysis was carried out (Fig. 19).

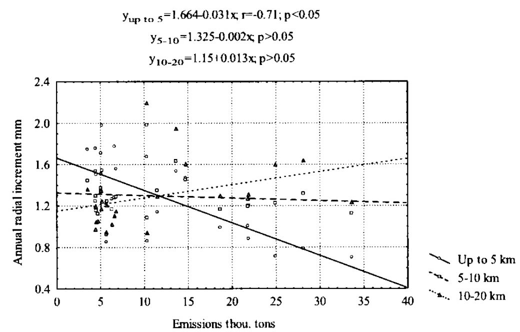


Fig. 19. The relationships between annual radial increment and emissions in the period of pollution reduction (1982-2005)

Results of the analysis have shown that due to reduction of "Achema" emissions radial increment of pine stands closest to the plant and damaged most considerably recovers most intensively. For more distant pine stands no linear relations between radial increment and amount of pollutants were found ($p>0.05$).

CONCLUSIONS

1. Investigations were carried out in pine stands of *Carico-sphagnosa* forest type growing under the impact of "Akmenės cementas" plant pollution and the following results were obtained:

1.1. Average temperature of active vegetation period 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.

1.2. 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 determined between plant emissions and radial increment of the most distant pine stands ($p>0.05$).

1.3. Multiple regression model including only the main components of pollution explains 62 % ($p<0.05$) of radial increment variation of pines closest to the plant. For the more distant pine stands models become statistically insignificant. When climatic factors are included into the models additionally, approximation level increases (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; $p<0.05$).

1.4. Intensity and duration of radial increment decrease during the period of intensive pollution is different for different distances from the pollution source. Period of radial growth depression for the closest pine stands lasted 11 years and radial increment decreased by 15 % on average ($p<0.05$) compared with the predicted increment norm. For pine stands at the distance of 5-10 km depression period lasted 5 years and increment losses amounted to 7 % on average ($p<0.05$) compared with the model.

1.5. It was determined, that since 1990 due to rapid decrease of plant emissions radial increment of the closest and most considerably damaged pine stands recovered most intensively and in last years was about 33 % higher than in the period of growth depression.

2. Investigations were carried out in pine stands of *Vaccinio-Myrtillosa* forest type growing under the impact of "Achema" plant pollution and the following results were obtained:

2.1. Radial increment increase in the habitats with normal moisture is induced by higher than long-term average temperature of winter (r=0.31-0.40; $p<0.05$) and spring months (r=0.26-0.39; $p<0.05$). Correlation analysis reveals positive influence of warm last year's October on the formation of radial increment (r=0.27; $p<0.05$).

2.2. Strong linear relations were determined between radial increment of pines at the distances of up to 5 km and 5-10 km and plant emissions (r equals to -0.81 and -0.47 respectively; $p<0.05$). Although correlation between the radial increment of most distant pine stands and total amount of pollutants is weak and insignificant, relation with mineral dust remains statistically significant (r=-0.51; $p<0.05$).

2.3. Multiple regression model including only the components of emissions describes 67 %, 43 % and 32 % of radial increment variation of pines growing at the distances up to 5 km, 5-10 km and 10-20 km from the plant respectively ($p<0.05$). Inclusion of climatic factors into the model reveals the significance of these factors to radial increment variation. However, the influence of pollution remains strong even for the most distant stands.

2.4. Investigation has shown that in the beginning of pollution positive effect of nitrogen compounds deposition stimulated pine growth at all distances (radial increment increased by 24 %, 17 % and 23 % respectively, compared to the predicted norm; $p<0.05$), but in the period of most intensive pollution the highest radial increment losses were observed in the closest stands (38 % compared to the predicted model; $p<0.05$).

2.5. The rate of recovery during the period of pollution reduction was the highest for the most damaged stands. In the last decade their radial increment exceeded the predicted norm statistically significantly by 21 % on average. Less damaged stands growing further from the plant had recovered earlier and their radial increment remained close to the model except the decrease in 1992-1994.

Generalizing the results of dendrochronological investigations of Scots pine (*Pinus sylvestris* L.) growing in the surroundings of "Akmenės cementas" and "Achema", it should be noted that:

- the largest radial increment changes and most considerable damage of pine stands due to local pollution are observed in the nearest surroundings of the plants (up to 5 km). However, results have shown that the impact of "Achema" pollutants reaches even the most distant pine stands situated 10-20 km away from the plant. This could be explained by the difference between the sizes of dust particles emitted by the plants. Cement dust particles, emitted by "Akmenės cementas", are larger and settle down more rapidly.
- the period of radial increment recovery for the most damaged stands lasted 5 years in the surroundings of "Akmenės cementas" and 8 years near "Achema". More intensive recovery of pines near "Akmenės cementas" was determined by the abrupt reduction of emissions twice as large as "Achema" emissions in the year of maximum pollution.
- Environmental pollution transforms the relations between radial increment and climatic factors. In the peat-bog soils under the impact of alkalizing pollution pines become more sensitive to the temperature, and their sensitivity to the amount of precipitation decreases. In the mineral soils under the impact of acidifying and eutrophying pollution the process is contrary: the increased pine sensivity to the amount of precipitation and only in some cases – to the temperature is observed.

LIST OF PUBLICATIONS

International publications in reviewed journals:

1. Vitas A., **Erlickytė R.** 2007. Influence of Droughts to the Radial Growth of Scots Pine (*Pinus sylvestris* L.) at Different Site Conditions. *Baltic Forestry*, 13 (1), p. 10-16. ISSN 1392-1355.

Publications in peer-reviewed Lithuanian journals included in the list certified by Department of Science and Higher Education:

1. Stravinskienė V., **Erlickytė R.** 2003. Klimato veiksnių poveikis paprastosios pušies (*Pinus sylvestris* L.) augimui AB „Akmenės cementas" aplinkoje. *Ekologija,* 3, p. 34-39. ISNN 0235-7224.
2. Stravinskienė V., Sujetovienė G., **Erlickytė R.** 2004. Miško augalijos rūšių įvairovė ir dirvožemio mikroelementinė sudėtis AB „Akmenės cementas" aplinkoje. *Ekologija,* 1, p. 46-53. ISNN 0235-7224.

Proceedings of conferences and workshops:

1. **Erlickytė R.** 2004. Klimato veiksnių ir antropogeninės taršos poveikis paprastosios pušies (*Pinus sylvestris* L.) augimui AB „Akmenės cementas" aplinkoje // 10-osios respublikinės studentų ir doktorantų mokslinės konferencijos „Žmogaus ir gamtos sauga" medžiaga [LŽŪU, 2004 m. gegužės 20-22 d.]. Kaunas: Akademija, p. 109-112.
2. Stravinskienė V., **Erlickytė R.**, Šimatonytė A. 2004. Growth and condition of Scots pine (*Pinus sylvestris* L.) forests in urban and industrial environment // Short materials of EuroDendro Conference of the European Working Group for Dendrochronology in honour of Prof. Dr. Dieter Eckstein on the occasion of his retirement [Rendsburg, Schleswig-Holstein, Germany, September 15-19, 2004]. Germany, p. 47-49.
3. **Erlickytė R.**, Stravinskienė V. 2007. Klimato veiksnių ir pramonės emisijų poveikis paprastosios pušies (*Pinus sylvestris* L.) metiniam radialiajam prieaugiui vietinės taršos zonoje // 10-osios jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis" medžiaga [VGTU, 2007 m. kovo 29 d.]. Vilnius.
4. Vitas A., **Erlickytė R.** 2007. Sausrų poveikis paprastosios pušies (*Pinus sylvestris* L.) metiniam radialiajam prieaugiui // 10-osios jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis" medžiaga [VGTU, 2007 m. kovo 29 d.]. Vilnius.
5. **Erlickytė R.**, Vitas A. 2007. Influence of droughts to the radial growth of Scots Pine (*Pinus sylvestris* L.) // Proceedings of International Young Scientist Conference „The Vital Nature Sign". Kaunas: VDU, p. 100-103. ISBN 978-9955-12-213-5.

CURRICULUM VITAE

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REZIUMĖ

Problemos aktualumas. Medžiai yra vieni jautriausių aplinkos būklės indikatorių, iš visų gyvybės formų labiausiai tinkamų aplinkos pokyčiams vertinti. Dėl lajų struktūros ypatumų medžiai glaudžiau kontaktuoja su atmosfera ir daugiau negu kitos augalijos formos filtruoja pernešamo oro masę, anatominiais ir morfologiniais požymiais indikuoja miško ekosistemų būklę. Jie lemia ekosferoje vykstančius procesus bei jautriai reaguoja į antropogeninius veiksnius, todėl integraliai atspindi klimato ir teršalų poveikį. Medžių, kaip pagrindinio miško ekosistemos komponento, augimas ir produktyvumas yra vieni geriausių indikatorių, atspindinčių bendrą miškų būklę ir ekologinę pusiausvyrą. Objektyviai įvertinę medžių būklę, galime spręsti ir apie gamtinės aplinkos būklę bei jos tinkamumą kitoms gyvybės formoms tarpti (Stravinskienė, 2002, 2005).

Labiausiai nukenčia arti taršos šaltinių augančios miško ekosistemos, kadangi vietinės taršos zonoje kenksmingų medžiagų koncentracija dažnai viršija ribines leistinas normas. Medžių pakenkimo intensyvumui turi įtakos ir teršiančių medžiagų koncentracija, jų poveikio trukmė bei į augalus patenkantis jų kiekis.

Žymūs medynų pažeidimai nustatyti įvairiuose šiaurės-vakarų Europos regionuose. Daugumos mokslininkų nuomone, miškų būklės blogėjimą lemia įvairių veiksnių kompleksas, tačiau pagrindinis veiksnys, lemiantis plataus masto miškų pakenkimus, yra aplinkos tarša, o kiti neigiami veiksniai tik sustiprina teršiančiųjų medžiagų poveikį (Bach, 1985; Innes, 1993; Chappelka, Freer-Smith, 1995; Nihlgard, 1997). Greta įvairių teršiančių medžiagų dažnai minimos ir nepalankios klimato sąlygos, miško kenkėjų invazijos, įvairios ligos bei miškininkavimo klaidos (Fuhrer, 1990; Auclair et al., 1992; Houston, 1992).

Lietuvoje didžiausią neigiamą įtaką miško ekosistemoms turi vietiniai taršos šaltiniai. Vienas didžiausiųjų vietinės taršos šaltinių – azotinių trąšų gamykla AB „Achema", kurios poveikio zonoje augančius miškus veikia ir rūgštinantys, ir eutrofizuojantys teršalai. Gausus gamyklos išmetamų teršalų (SO_2, NO_x, NH_3 ir kt.) kiekis prieš dvidešimtmetį sukėlė aplinkinių miškų dirvožemio rūgštėjimą ir intensyvų medynų džiūvimą. Sumažėjus teršalų emisijai, prasidėjo miško ekosistemų atsikūrimo procesas, tačiau pastarųjų metų miškų monitoringo rezultatai rodo, kad gretimų miškų dirvožemiai ir toliau rūgštėja (Armolaitis, 1998; Armolaitis ir kt., 1999a; Armolaitis, Stakėnas, 2001).

Šarminančių dalelių iškritos vaidina svarbų vaidmenį ne tik dėl jų gebėjimo neutralizuoti rūgštinančius junginius, bei ir kaip svarbios augalams maisto medžiagos (Gorham, 1994; Draaijers et al., 1996). Technogeninių dulkių poveikis augalų bendrijoms nesulaukė tiek daug mokslininkų dėmesio, kaip SO_2, NO_x ar kitų teršalų poveikio tyrimai, kadangi šarminanti tarša dažniausiai yra vietinio pobūdžio. Nors ši problema nėra nauja, tačiau iki šiol nėra išaiškintas poveikio mechanizmas, atsako pobūdis, ekosistemų pažeidžiamumas ir tolerantiškumas. Šarminančios dulkės, išmetamos iš AB „Akmenės cementas" gamyklos, neutralizuoja aplinką rūgštinančius teršalus (SO_2, NO_x) ir ją šarmina.

Nuo pirmųjų miškų monitoringo metų Lietuvoje atliekamas dendrochronologinis monitoringas – aplinkos būklės indikacijai naudojama medžių rievių teikiama informacija apie ekologines bei klimatines vietovės sąlygas, aplinkoje vykstančius reiškinius. Medžių rievės, jų plotis ir struktūra integraliai atspindi kompleksinį aplinkos veiksnių poveikį (Lovelius, 1997).

Tikslas – ištirti paprastosios pušies (*Pinus sylvestris* L.) medynų radialiojo prieaugio pokyčius vietinės šarminančios, rūgštinančios ir eutrofizuojančios taršos poveikio zonose bei radialiojo prieaugio atsikūrimo dėsningumus sumažėjus taršos poveikiui.

Siekiant šio tikslo buvo iškelti ir įvykdyti tokie **uždaviniai:**

- išanalizuoti klimato veiksnių įtaką sąlyginai švarioje aplinkoje augančių pušų metinio radialiojo prieaugio formavimuisi;
- ištirti skirtingu atstumu nuo taršos šaltinio augančių pušų metinio radialiojo prieaugio pokyčius priklausomai nuo taršos intensyvumo;
- ištirti kompleksinį klimato veiksnių ir pramonės taršos poveikį pušų augimui;
- įvertinti antropogeninius prieaugio pokyčius vietinės taršos sąlygomis;
- išanalizuoti pušų atsikūrimo procesus sumažėjus gamyklos teršalų emisijai.

Mokslinis naujumas. Pirmą kartą Lietuvoje atlikti išsamūs dendrochronologiniai klimato veiksnių ir pramonės taršos poveikio paprastosios pušies (*Pinus sylvestris* L.) metiniam radialiajam prieaugiui tyrimai „Akmenės cemento" poveikio zonoje; analizuotas cemento dulkių poveikis paprastosios pušies metiniam radialiajam prieaugiui; įvertinti antropogeniniai radialiojo prieaugio pokyčiai „Akmenės cemento" ir „Achemos" vietinės taršos sąlygomis bei sumažėjus aplinkos taršai; atlikta detali pušų metinio radialiojo prieaugio atsikūrimo dėl pramonės taršos sumažėjimo analizė; ištirta, kaip pramonės tarša iškreipia metinio radialiojo prieaugio ryšius su klimato veiksniais.

IŠVADOS

1. Atlikus tyrimus „Akmenės cemento" poveikio zonoje augančiuose raistašilio (*Carico-sphagnosa*) miško tipo pušynuose, gauti šie rezultatai:

1.1. Durpinėse pelkinėse (tarpinės pelkės) augavietėse teigiamos įtakos pušų radialiojo prieaugio formavimuisi turi aukštesnė nei vidutinė daugiametė aktyvios vegetacijos laikotarpio oro temperatūra (r=0,22-0,34; p<0,05), o didesnis nei vidutinis daugiametis liepos mėnesio kritulių kiekis lemia radialiojo prieaugio mažėjimą (r=-0,25; p<0,05).

1.2. Nustatytas tiesinis ryšys tarp arčiau gamyklos augančių pušų radialiojo prieaugio ir gamyklos teršalų kiekio: r=-0,62 iki 5 km ir r=-0,49 – 5-10 km atstumu (p<0,05). Tarp tolimiausių pušų prieaugio ir teršalų kiekio ryšio nenustatyta (p>0,05).

1.3. Daugiaveiksnės regresijos modelis, įtraukiantis tik gamyklos teršalus, aprašo 62 % (p<0,05) artimiausių pušų radialiojo prieaugio svyravimų; tolimiausiems medynams modelis tampa statistiškai nepatikimas. Į regresijos modelius įtraukus klimato veiksnius, radialiojo prieaugio svyravimai aprašomi tiksliau (determinacijos koeficientas R^2=0,70 (iki 5 km) ir R^2=0,57 (5-10 km atstumu); p<0,05).

1.4. Intensyvios taršos laikotarpiu radialiojo prieaugio sumažėjimo intensyvumas ir trukmė skirtingu atstumu nuo taršos šaltinio buvo nevienoda. Arčiausiai gamyklos augančių ir labiausiai pažeistų pušų radialiojo prieaugio depresijos laikotarpis tęsėsi 11 metų, o prieaugis sumažėjo vidutiniškai 15 % (p<0,05) lyginant su prognozuota norma. 5-10 km atstumu nuo gamyklos augančių pušų prieaugio sumažėjimas truko 5 metus, o nuostoliai siekė vidutiniškai 7 % (p<0,05) lyginant su prognozuota prieaugio norma.

1.5. Nustatyta, kad nuo 1990 m. mažėjant gamyklos emisijai artimiausioje gamyklos aplinkoje augančių, labiausiai pažeistų medynų radialusis prieaugis atsikūrė intensyviausiai ir paskutiniaisiais metais buvo apie 33 % didesnis nei didžiausio nuosmukio laikotarpiu.

2. Atlikus tyrimus „Achemos" poveikio zonoje augančiuose žaliašilio (*Vaccinio-myrtillosa*) miško tipo pušynuose, gauti šie rezultatai:

2.1. Radialiojo prieaugio didėjimą normalaus drėgnumo augavietėse skatina aukštesnė nei vidutinė daugiametė žiemos mėnesių (r=0,31-0,4; p<0,05) ir pavasario (r=0,26-0,39; p<0,05) oro temperatūra. Gauti rezultatai išryškina teigiamą šilto vienerių ankstesnių metų spalio mėnesio įtaką radialiojo prieaugio formavimuisi (r=0,27; p<0,05).

2.2. Tiesinis ryšys nustatytas tarp arčiausiai (iki 5 km) ir 5-10 km atstumu nuo gamyklos augančių pušų radialiojo prieaugio ir gamyklos teršalų kiekio (atitinkamai r=-0,81 ir r=-0,47; p<0,05). Nors nustatyta silpna ir nepatikima 10-20 km atstumu nuo gamyklos augančių pušų prieaugio priklausomybė nuo bendro teršalų kiekio, tačiau ir šiuo atstumu ryšys su mineralinėmis gamyklos dulkėmis išlieka statistiškai patikimas (r=-0,51; p<0,05).

2.3. Daugiaveiksnės regresijos modelis, įtraukiantis tik gamyklos teršalus, aproksimuoja 67 % iki 5 km, 43 % – 5-10 km ir 32 % – 10-20 km atstumu nuo gamyklos augančių pušų radialiojo prieaugio svyravimų (p<0,05). Į kompleksinį modelį įtraukus klimato rodiklius, išryškėja klimato veiksnių įtaka prieaugio kitimui, tačiau taršos poveikis išlieka net ir toliausiai nuo gamyklos augantiems medynams.

2.4. Tyrimai parodė, kad taršos pradžioje teigiamas azoto junginių poveikis medynų radialiajam prieaugiui skatino pušų augimą visais atstumais (prieaugis padidėjo atitinkamai 24 %, 17 % ir 23 % lyginant su prognozuota prieaugio norma; $p<0{,}05$), tačiau intensyviausios taršos laikotarpiu didžiausi prieaugio nuostoliai stebimi artimiausiuose medynuose (38 % lyginant su prognozuota prieaugio norma; $p<0{,}05$).

2.5. Mažėjant taršai intensyviau atsikūrė artimiausi medynai; jų radialusis prieaugis paskutiniuoju dešimtmečiu statistiškai reikšmingai viršijo apskaičiuotą prieaugio normą vidutiniškai 21 %. Mažesnius prieaugio nuostolius depresijos laikotarpiu patyrę toliau nuo gamyklos augantys medynai atsikūrė anksčiau ir, išskyrus 1992-1994 m. sumažėjimą, svyravo apie apskaičiuotą prieaugio normą.

Apibendrinant „Akmenės cemento“ ir „Achemos“ aplinkose augančių paprastosios pušies (*Pinus sylvestris* L.) medynų dendrochronologinių tyrimų rezultatus, pažymėtina, kad:

- didžiausi radialiojo prieaugio pokyčiai ir stipriausi pušynų pažeidimai dėl vietinės taršos stebimi artimiausioje gamyklų aplinkoje (iki 5 km). Tačiau rezultatai rodo, kad „Achemos“ teršalų poveikis išlieka net ir toliausiai nuo gamyklos (10-20 km) augantiems medynams. Tai gali būti paaiškinama skirtingu gamyklų išmetamų dulkių dalelių dydžiu. „Akmenės cemento“ išmetamų cemento dulkių dalelės yra didesnės, trumpiau išsilaiko atmosferoje ir greičiau nusėda.
- arčiausiai gamyklų augančių ir labiausiai pažeistų pušynų radialiojo prieaugio atsikūrimo trukmė buvo nevienoda: „Akmenės cemento“ aplinkoje – 5 metai, „Achemos“ – 8 metai. Intensyvesnį radialiojo prieaugio atsikūrimą „Akmenės cemento“ aplinkoje lėmė staigus net dvigubai didesnio nei „Achemos“ intensyvios taršos metais išmestų teršalų kiekio sumažėjimas.
- aplinkos tarša pakeičia radialiojo prieaugio ryšius su klimato veiksniais. Pelkiniuose dirvožemiuose šarminės taršos poveikyje pušys tampa jautresnės temperatūrai, o jų jautrumas kritulių kiekiui sumažėja. Mineraliniuose dirvožemiuose rūgštinančios ir eutrofizuojančios taršos poveikyje – atvirkščiai: žymiai padidėja pušų jautrumas kritulių kiekiui ir tik kai kuriais atvejais – temperatūrai.

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Regina Erlickytė

REGULARITIES OF SCOTS PINE (*Pinus sylvestris* L.) RADIAL INCREMENT FORMATION DUE TO VARIATION OF EMISSIONS OF "AKMENĖS CEMENTAS" AND "ACHEMA" PLANTS

Summary of Doctoral Dissertation

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