TREE-RING ANALYSIS FOR THE ASSESSMENT OF ANTHROPOGENIC CHANGES AND TRENDS

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Abstract. Investigation of Pine (*Pinus sylvestris* L.) annual radial increment (width of annual tree rings) was carried out in the surroundings of one of the largest pollution sources in Lithuania – Jonava Nitrogen Fertilizers Plant. The main objective of investigation was to analyse different sides of anthropogenic transformations of tree-ring series in the polluted environment: changes in tree growth intensity; variance changes in tree-ring series; changes in the relations with natural external factors. Three different periods of tree reaction to the environmental pollution were singled out – fertilization period, depression period and recovery period since annual emissions were essentially reduced. The variance of tree-ring series has increased several times in the polluted environment. Reaction of trees to the impact of climatic factors (temperature, precipitation) has changed significantly in the polluted environment and their sensitivity has also increased.

Keywords: anthropogenic changes, environmental pollution, predictive capacity, tree-ring series

1. Introduction

Forest ecosystems comprise a very important component of the ecosphere and their role in the turnover of materials and energy is crucial for the state of the ecosphere. Along with the increase in the anthropogenic impact and, first of all, with the increase in environmental pollution, environmental role of forest ecosystems became especially significant. Taking into account an exceptional environmental and economic value of forests on the one hand, and their sensitivity to the environmental pollution on the other hand, forest ecosystems could be considered as one of the most appropriate objects of environmental monitoring and assessment, capable of characterizing the general state and anthropogenic trends of the entire ecosphere.

Growth and productivity of trees, as the main component of forest ecosystems, is one of the best indicators, able to reflect the general health and sustainability of forests. The anatomic structure of trees creates unique possibilities for the retrospective assessment of growth rate for a long retrospective period based on annual tree-ring analysis.

As it was noticed by Eckstein (1985), tree-ring analysis was applied for studies of local forest damage already more than a hundred years ago. However, this technique became more common at the beginning of the 1970s following heavy environmental pollution (Vinš, Mrkva, 1973; Philips *et al.*, 1977). An additional

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impulse for the development and modernization of tree-ring analysis methods was given at the very beginning of the 1980s, when forest damage was recognized as a deeper and wider problem on regional scale (Eckstein, 1985; Cook, 1987a,b; Innes, Cook, 1989; Schulce, 1989). Long-range transboundary pollution and environmental acidification effects were considered as new and very powerful external factors, considerably affecting the health and productivity of forests (Knabe, 1981; Bauer, 1982; Hosker, Lindber, 1982; Braker, Gagen, 1984; Pollanschutz, 1987; Jones, 1989; Mehne-Jakobs, 1990).

From the beginning of the 1990s, after the collapse of the Soviet block, along with transitional economy decline in East-European countries, environmental pollution was considerably reduced (Juknys, 1995; Žukauskas *et al.*, 1996) and recovery of damaged forests has started on a local (Stravinskiene, 1995) and later – on a regional (Armolaitis, 1998; Ozolinčius, Stakėnas, 1999) scale. Tree-ring analysis could serve as a very useful tool for the quantitative assessment of these positive trends as well (Kairiukstis *et al.*, 1987; Kairiukstis and Stravinskiene, 1992; Juknys and Jančys, 1998).

It must be noted, that the duration of observations and measurements is very important for the detection and assessment of anthropogenic changes in monitored indicators. Having in mind, that quite often erroneous conclusions can be arrived at with accurate, but short term data, methods and indicators should have a high priority to allow the use of retrospective information for a sufficiently long period.

Despite moderate sensitivity and powerful homeostatic mechanisms of trees, retrospective tree-ring analysis provides a very useful long term environmental information. Methods based on the quantitative analysis of tree-ring series of injured stands and the dependence of growth rate (width of annual rings) on different external factors are most promising (Eckstein, 1985, 1987; Cook, 1987b; Schweingruber, 1989, 1996).

The main objective of investigation presented in this article was to analyse different sides of anthropogenic transformations of tree ring series in the polluted environment:

– changes in the annual tree increment;
– changes in tree-ring series variance;
– changes in the relations with natural external factors.

2. Materials and Methods

Main investigations were carried out in the surroundings of one of the largest pollution sources in Lithuania – Jonava Nitrogen Fertilizers Plant 'Achema' (former "Azotas"), situated in the central part of Lithuania. Pine (*Pinus sylvestris L.*) forests prevail in this region. "Achema" started producing fertilizers in 1965 and was gradually expanding till 1978, when the most polluting Nitrophosca department was constructed, and total annual emissions reached almost 40 thousand tons.

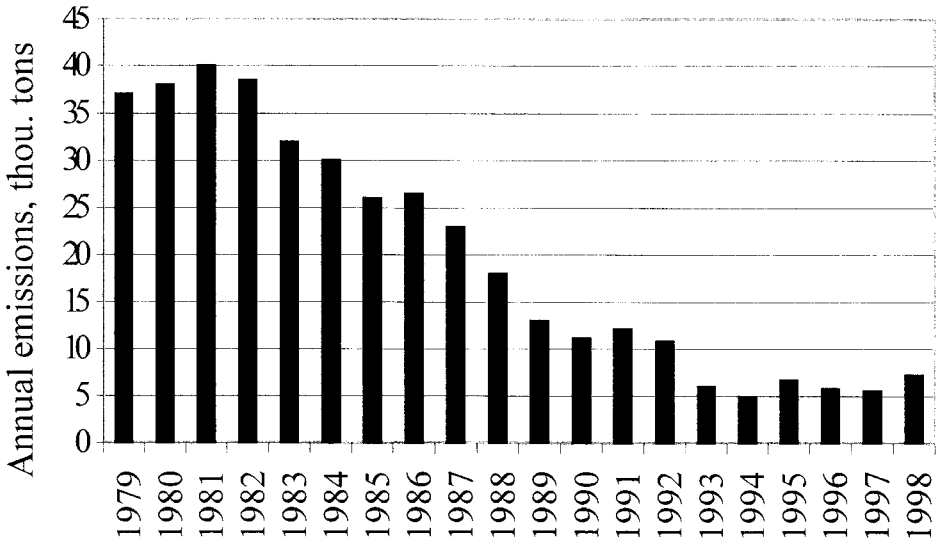


Figure 1. Total annual emissions of 'Achema' (thousand tons).

The first signs of local forest damages were noticed already in 1972, but extremely acute this problem became since 1979, when after a very hard winter obvious signs of forest damage in the direction of prevailing winds were recorded up to 10–12 km, and at a distance of 2–3 km from the pollution source coniferous forests were completely died.

Despite essential reduction of emissions which started at the beginning of the 1980s (Figure 1), when different pollution mitigation measures were implemented in 'Achema', the zone of damaged forests in the direction of prevailing winds expanded up to 20–25 km at the end of the 1980s.

An additional input to the reduction of emissions was a serious accident in the most polluting Nitrophosca department in 1989 and this department was closed. As seen from Figure 1, total annual emissions of 'Achema' from the beginning of the 1980s up to the end of the1990s were reduced almost eight times. In 1997 total emissions of 'Achema' comprised 5.5 thousand tons and in 1998 an increase in emissions up to 7.0 thousand tons was recorded.

The composition of aerial emissions has also changed during this period. In 1979, when the total amount of annual emissions was 37 thousand tons, carbon monoxide comprised 26.5%, sulphur dioxide – 12.4%, nitrogen oxides - 10.3%, ammonia – 10.1% and mineral dust – 37.3%. In the emissions of 1997 the input of carbon monoxide was rather bigger and made up 66.0%. The input of other pollutants has essentially decreased and sulphur dioxide comprised 9.7%, nitrogen oxides – 7.6%, ammonia – 11.3% and mineral dust – 2.4%.

As a consequence of such an essential decrease in 'Achema's' emissions, annual total load of sulphur (wet and dry) during the last decade was reduced almost ten

times near the source of pollution and approximately three times at a distance of 10–20 km in the direction of prevailing winds. The decrease in total nitrogen load was less essential. A 4-5-fold decrease in annual nitrogen load was recorded at a distance of 0–5 km, and approximately two-fold reduction at a distance of 10–20 km (Armolaitis, 1998).

After such considerable abatement of environmental pollution, the first obvious signs of forest recovery in the surroundings of 'Achema' were noticed at the beginning of the 1990s. Given a big lack of sound knowledge regarding the resistance of damaged trees and possibilities of their recovery under reduced environmental pollution, a joint project with the participation of environmental and forestry specialists from Vytautas Magnus University, Lithuanian Forest Research Institute and Lithuanian Agricultural University was funded by Lithuanian State Science and Study Foundation and started in 1998.

The first results regarding anthropogenic changes in tree growth during the periods of damage and recovery are presented in this article.

Three-stage sampling pattern was used for the collection of field materials: 1) sampling of research stands; 2) sampling of circular plots within each sampled research stand; 3) sampling of trees for more detailed measurements and tree ring analysis.

Twelve circular sample plots were established in each sampled stand. Sample plots were distributed in a systematic way – according to a square network. The place of the first sample plot was chosen randomly. The area of circular sampling plots is determined to contain on average 15–20 trees. The diameter at breast height was measured for all trees inside circular plots. Considering sampling intensity, the standard error of stand volume should not exceed 10%, while the standard error of the average diameter – 5% ($p < 0.05$).

During the third sampling stage three trees being closest to the center of circular sample plot were sampled and main stem and crown parameters (diameter, height) were measured. For trees of dominant and co dominant class, being without obvious injury, wood samples have been taken by a special borer for analysing annual rings of trees. The mean tree-ring series for each stand were calculated on the basis of tree-ring series of 30–36 sampled trees.

Eight damaged semimature (80–90 yr old) Pine (*Pinus sylvestris*) stands, situated at different distances from the pollution source (2.7–21.6 km) in the direction of prevailing winds were selected for this study. For comparison, three relatively healthy semimature Pine stands were sampled and measured according to the same sampling design at a distance of 50–55 km against the prevailing winds under similar site conditions.

In order to assess anthropogenic changes in the increment of trees it is important to evaluate what normal growth of them would have been, i.e. how the trees would have grown if the environment had not been polluted. For this the method of multiple climate response models has been applied. These models are based on the dependence of ring width of trees on climatic factors. The average monthly tem-

peratures and monthly precipitation are usually treated as the main factors (Fritts, 1976; Cook, 1987a, b; Eckstein, 1985, 1989). For these investigations the climatic data obtained from Jonava meteorological station have been applied, which is at a distance of 15 km from the stands investigated. In assessing the changes in the increment of trees in the polluted environment tree-ring series have been divided into two periods – prior to the construction of the plant and after its construction. Multidimensional regression model has been constructed according to the first (calibration) part of the series. Further, by including the values of selected climatic factors of the second period in this model it has been predicted how the trees would have grown if the plant had not been constructed and atmospheric pollution had not started. In accordance with the difference between the actual values and these estimated by the model the effect of environmental pollution on tree growth has been assessed.

Prior to the construction of the multidimensional regression model the series of the annual radial increment were standardized, i.e. they were transformed so that the mean of the series was constant. Since with the aging of trees the increment tends to diminish the dependence of the increment on age has been approximated according to the exponential function. After dividing the measured values of the increment by the values of age trend we calculated increment indexes, which were used in constructing multidimensional regression models of the dependence of the increment on climatic factors. However, for more vivid presentation (Figures 2 and 3) of the data the values of increment indexes were again transformed into actual values of the increment. In all regression models that are presented the first two members of the equation describe the exponential function of age trend of the annual increment.

For the deriving of regression equation between the increment indexes and climatic factors first we calculated the correlation between the indexes and climatic factors by using the data on the period prior to the construction of the plant. The indicators of climate were included in the regression model by a stepwise method. To assess the quality of the models and to compare them we used adjusted coefficient of determination AR^2. Climatic factors are included in the model as long as the including of a new variable significant reduces AR^2.

In order to assess the accuracy of the method the data on the control stands, i.e., on the stands conditionally growing in the relatively unpolluted environs have been applied. For this in accordance with the data on the second (prediction) period the error of prediction of the increment has been estimated in per cent:

$$\mathrm{Sp} = 100^* \sqrt{(1/n) \sum_{t=k+1}^{k+n} ((Y_t - W_t)/W_t)^2} \tag{1}$$

where y_t – the actual values of the increment; w_t – estimated values of the increment according to the model.

In studying anthropogenic changes in the variance of increment series and in the correlation between the increment and climatic factors in the polluted environment the series of the increment have also been divided into two different periods – before starting the production of fertilizers in 'Achema' (till 1965) and when the production being concomitant of atmospheric pollution began. In these cases also standardized increment series, i.e. their indexes have been used.

3. Results and Discussion

As mentioned in the introduction, anthropogenic changes in the annual radial increment (tree-ring width), changes in the variance of tree-ring series and these in the relations with natural external factors in the polluted environment are analysed in this article.

3.1. Anthropogenic Changes in the Annual Radial Increment

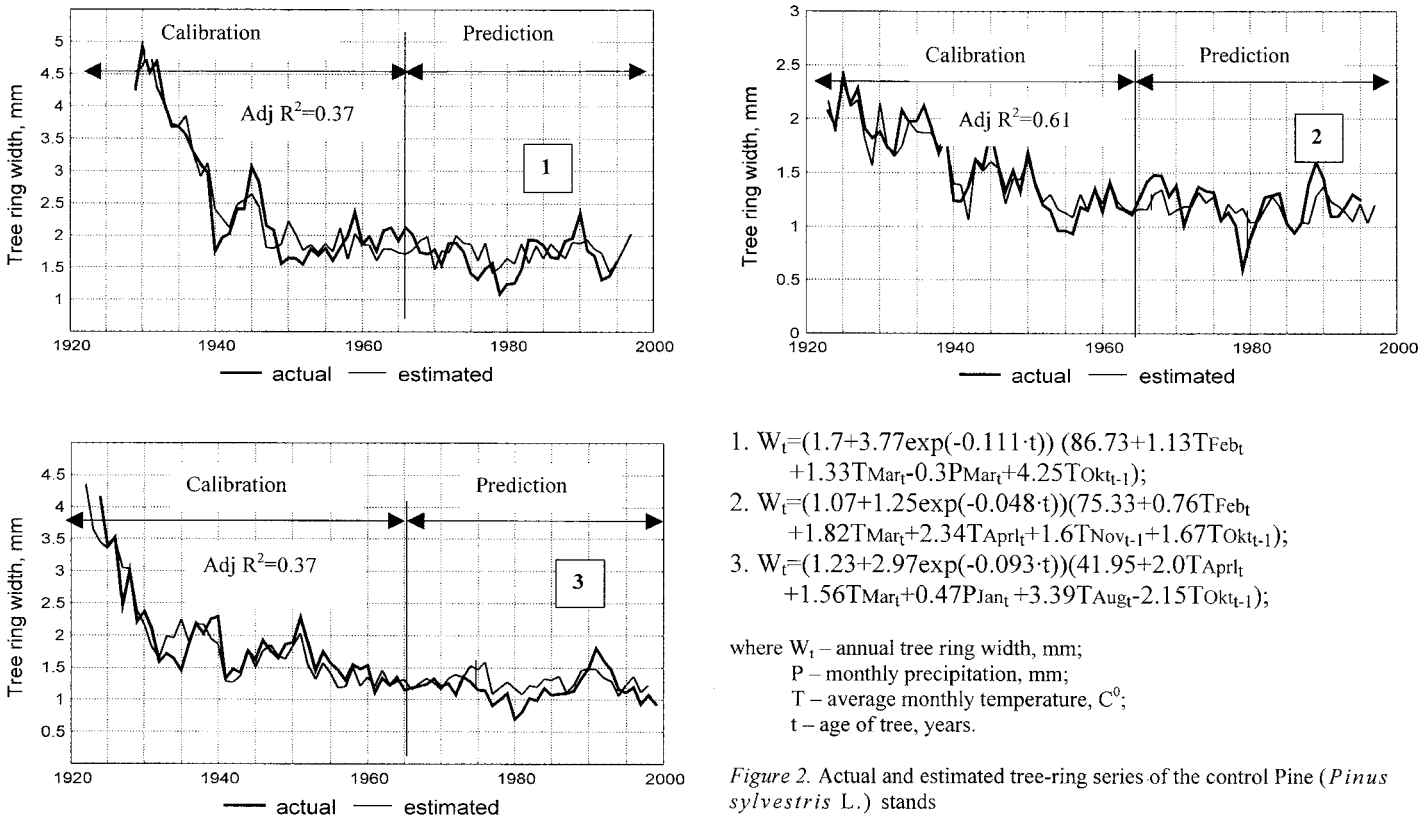
Multiple climate response models are used as the main tool for the assessment of anthropogenic changes in the annual tree increment. The main priority of this method – long term data are used most effectively. On the basis of very accurate but short term data erroneous conclusions can be made, unless temporal quasiperiodical fluctuations of monitored indicators are not considered.

Our earlier investigations (Juknys, 1994; Juknys and Vencloviene, 1998) have shown, that the temperatures of late winter (February), early spring (March, April) and these of late summer (August) affect the Pine growth rate most strongly in our latitudes. In some cases the temperatures of past year autumn months (September, October) have an essential impact on the radial increment of trees. The impact of precipitation is less significant in our latitudes. The closest relationships were found between the annual radial Pine increment and precipitation of late winter (February) and summer (June, July).

Taking into account, that in our investigation the prediction of normal annual increment as a basis for the quantitative assessment of its anthropogenic changes should be made for a rather long period (33 yr), first of all the possibilities of this method were additionally checked on tree-ring series of relatively healthy Pine stands sampled as the control.

Actual and estimated data of tree ring-series for the control stands are presented in Figure 2. As illustrated by the data, 4–6 climatic factors prove to be statistically significant ($p < 0.05$) and 37–67% of tree-ring series variance can be explained by climatic factors included into multiple climate response models. The list of included climatic factors is rather typical of the climatic conditions of Lithuania. The temperatures of late winter and early spring, precipitation of winter as well as the temperatures of past autumn are prevailing in this list.

As seen from Figure 2, actual and estimated tree ring series of control (relatively undamaged) stands for the prediction period fit rather well and elaborated models



1. $W_t=(1.7+3.77\exp(-0.111\cdot t))\,(86.73+1.13T_{Feb_t}+1.33T_{Mar_t}-0.3P_{Mar_t}+4.25T_{Okt_{t-1}})$;
2. $W_t=(1.07+1.25\exp(-0.048\cdot t))(75.33+0.76T_{Feb_t}+1.82T_{Mar_t}+2.34T_{Aprl_t}+1.6T_{Nov_{t-1}}+1.67T_{Okt_{t-1}})$;
3. $W_t=(1.23+2.97\exp(-0.093\cdot t))(41.95+2.0T_{Aprl_t}+1.56T_{Mar_t}+0.47P_{Jan_t}+3.39T_{Aug_t}-2.15T_{Okt_{t-1}})$;

where W_t – annual tree ring width, mm;
P – monthly precipitation, mm;
T – average monthly temperature, C^0;
t – age of tree, years.

Figure 2. Actual and estimated tree-ring series of the control Pine (*Pinus sylvestris* L.) stands

Figure 2. Actual and estimated tree ring series of the control Pine stands.

prove to be an acceptable tool for the assessment of possible anthropogenic changes in tree-ring width. For the quantitative assessment of resolving capacity of climate response models, standard prediction error was calculated for different prediction periods. Three different prediction periods of 10, 20 and 30 yr were examined during this exercise. Standard prediction error for a period of ten years was set at from 7.6 to 11.3%, for twenty-year prediction period 10.7–14.6% and for a period of thirty years 12.5–16.1%.

Such a general conclusion can be drawn from the obtained results – the resolving capacity of climate response models decreases with increasing prediction period. In the case of prediction for a period of 10 yr, the standard error does not usually exceed 10% and in the case of prediction for a longer (20–30 yr) period, anthropogenic changes in the increment not less than 15% could be assessed statistically reliably.

Parameters of climate response models of eight damaged stands were calculated on the basis of the first part of tree-ring series (until 1965, when 'Achema' was started). Obtained multiple regression models are presented below:

L= 2.7 km. $W_t = (1.15 + 3.1e^{-0.009t})(143.02 + 0.23\ P_{Jun_t} + 1.61\ T_{Feb_t}\ 3.23\ T_{Aug_{t-1}} + 1.91\ T_{Nov_{t-1}})$;

L = 3.2 km. $W_t = (1.36 + 1.11e^{-0.047t})(110.5 + 1.92\ T_{Feb_t} - 0.15\ P_{Okt_{t-1}} - 1.08\ T_{Jan_t})$;

L = 6.0 km. $W_t = (1.21 + 4.6e^{-0.073t})(144.1 - 3.77\ T_{Aug_{t-1}} + 0.52\ P_{Jan_t} + 0.09\ P_{Aug_t})$;

L = 6.5 km. $W_t = (1.28 + 2.05e^{-0.04t})(55.46 + 2.08\ T_{Mar_t} + 2.4T_{Okt_{t-1}} + 0.91\ T_{Jan_t} + 2.0\ T_{Aug_t})$;

L = 10.9 km. $W_t = (1.13 + 4.91e^{-0.095t})(105.3 + 2.14T_{Mar_t} + 3.16\ T_{Okt_{t-1}} + 1.99\ T_{Apr_t} - T_{Aug_{t-1}})$;

L = 11.4 km. $W_t = (1.13 + 3.78e^{-0.097t})(144.93 + 1.41\ T_{Feb_t} - 1.97\ T_{Aug_{t-1}} + 0.2\ P_{Jan_t} - 1.76\ T_{Apr_t})$;

L = 20.6 km. $W_t = (1.44 + 2.77e^{-0.102t})(34.85 + 1.05\ T_{Feb_t} + 3.18\ T_{Apr_t} + 2.9\ T_{Jul_t})$;

L = 21.3 km. $W_t = (1.28 + 4.93e^{-0.08t})(33.41 + 1.17\ T_{Feb_t} + 2.39\ T_{Maj_t} + 2.0\ T_{Nov_{t-1}} + 2.18\ T_{Aug_{t-1}})$,

where L – distance to pollution source, km; P – monthly amount of precipitation, mm; T – average monthly air temperature, C°; t – age of a tree, years.

As seen from the presented climate response models, in this case 3–6 climatic factors are also included into the models and 36–63% of tree-ring series variance is attributed to the impact of included climatic factors.

Some examples of actual and estimated data of tree ring-series for damaged Pine stands are presented in Figure 3. As seen from the data (Figure 1), since 1965, when 'Achema' started producing fertilizers, emitted nitrogen compounds had a positive impact, and annual increment increased, as compared with the normal growth. This period is named as fertilization period. However, several years later the general impact of increased emissions became negative and growth depression period started. A very rapid decrease in the annual increment can be observed since 1979, when the most polluting Nitrophosca department started and environmental

pollution essentially increased. The exclusively cold winter of 1978/79 was an additional unfavourable external factor in this case.

The third period – recovery of damaged stands started in the mid – 1980s as a consequence of different pollution mitigation measures introduced and environmental pollution was reduced (Figure 1).

As seen from data presented in Figure 3, the intensity and duration of fertilization and depression periods are rather different for Pine stands situated at different distances from the pollution source. The cases of statistically significant anthropogenic changes of the annual radial increment ($p < 0.05$) are marked by vertical dashes.

As the data presented in Figure 4 illustrates, the period of fertilization had a different duration for damaged stands situated at different distances from the pollution source. The range of fertilization period is from 5 yr for the most distant pine stands up to 8 yr for the closest ones.

The duration of depression period differed even more at various distances (Figure 5). This period exceeded 10 yr for the closest and most damaged stands and came down to 4 yr for stands situated 20–21 km away from the pollution source.

The average increase in the tree-ring width during the period of fertilization constituted 20–30%, as compared with predicted normal growth. No statistically significant differences in changes in the annual increment at different distances from 'Achema' were found. Possibly, closer to the polluting source, some partial depression of tree growth took place from the very beginning because of higher concentrations of pollutants.

However, the average decrease in the annual increment during the period of depression was rather different at various distances from the pollution source. The average losses of the radial increment comprised 40–45% for the closest and most damaged Pine stands, and 20 – 25% for the most distant stands.

The process of recovery is rather different for differently damaged stands. As seen from Figure 3, stands with less depression of tree growth have reached a normal level of the annual increment in the mid – 1980s. In the most considerably damaged Pine stands recovery of the annual increment up to the normal level took place only at the very end of the 1980s. However, over the last 3–4 yr the most intensive recovery of growth rate and even excess of the predicted normal annual increment can be observed just in the Pine stands damaged most considerably.

At the same time some additional depression of the growth has been rather obvious for the most distant stands during the last few years. Redistribution of air pollution after the reconstruction of 'Achema' could be a cause of this phenomenon. Monitoring of air pollution conducted within the same project has shown, that maximal concentrations of sulphur dioxide were registered at a distance of 15 km from the pollution source during last several years.

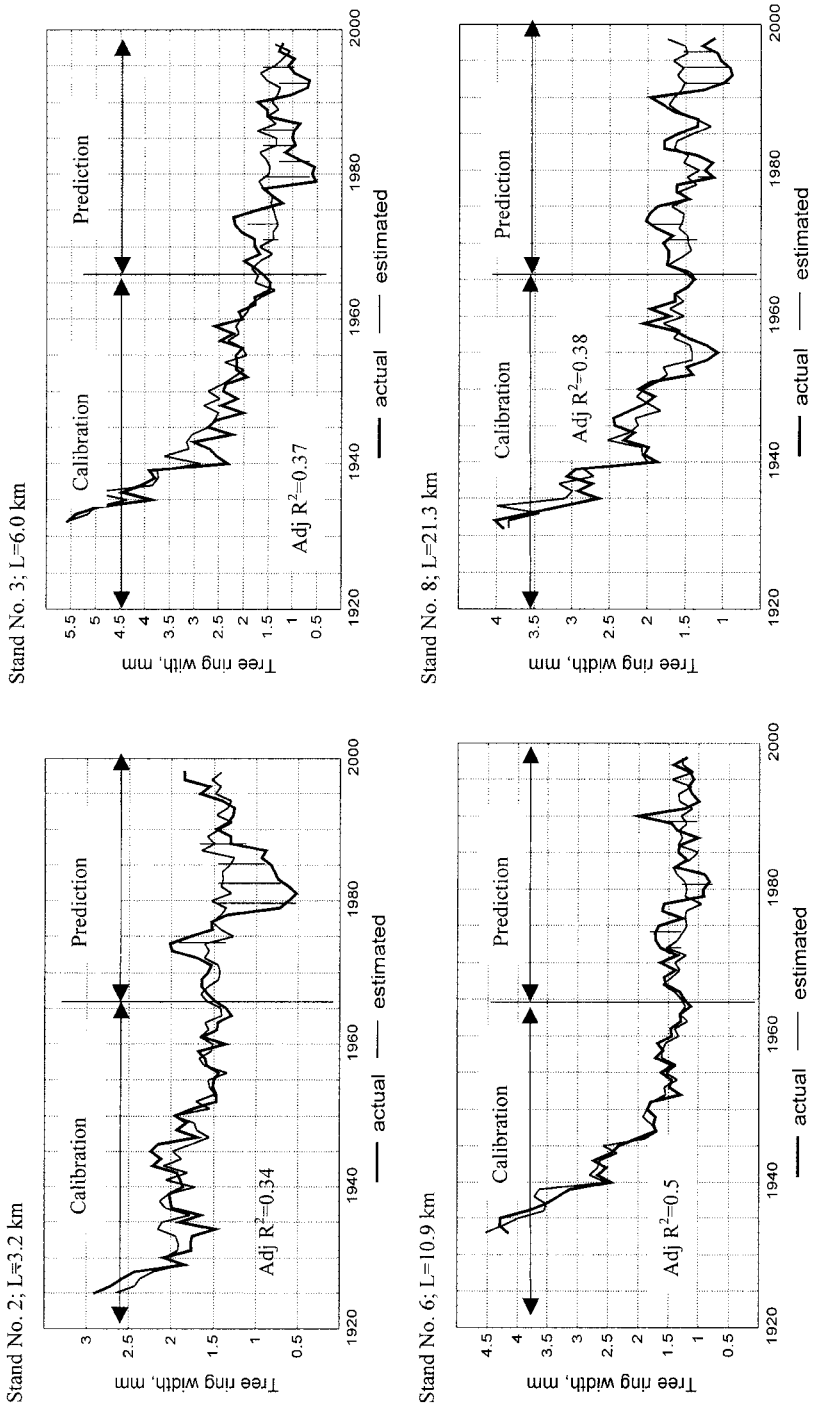


Figure 3. Actual and estimated tree-ring series of damaged Pine stands.

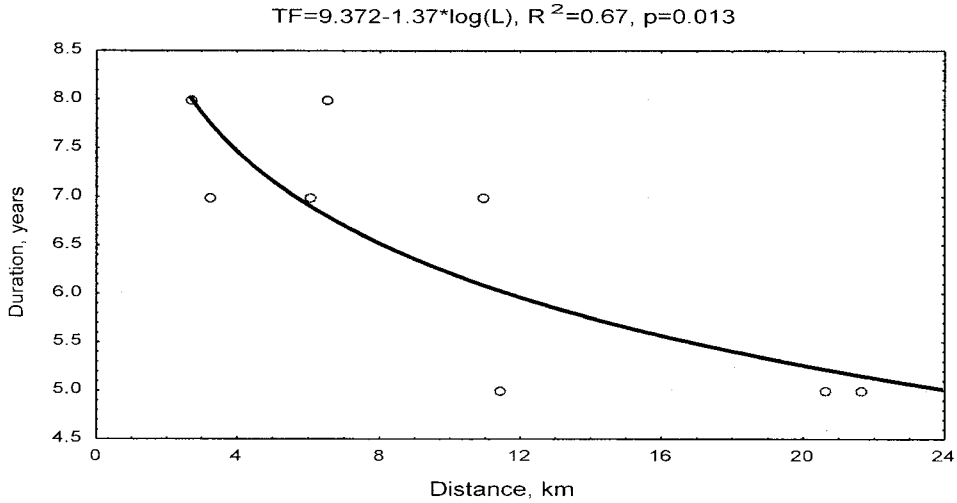


Figure 4. Duration of fertilization period (TF) at different distances (L) from the pollution source.

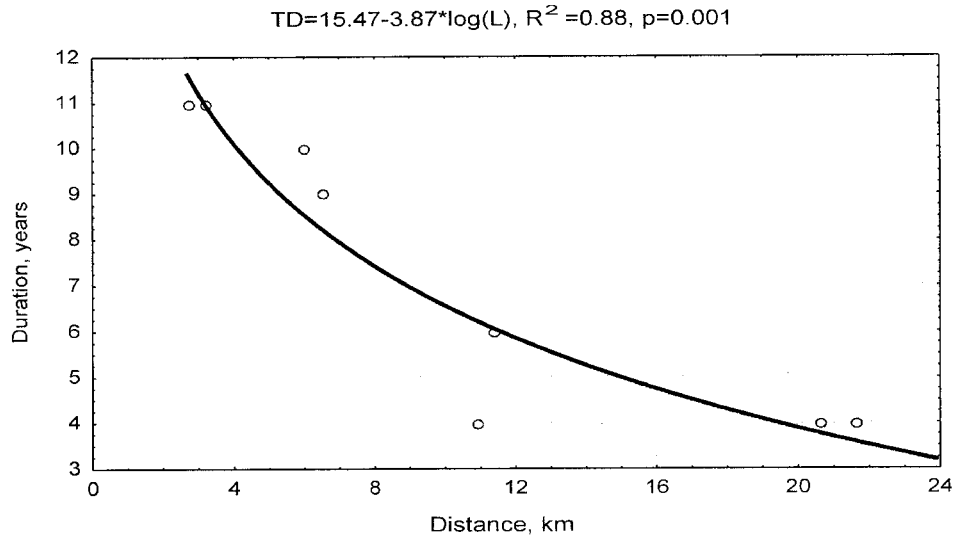


Figure 5. Duration of depression period (TD) at different distances (L) from the pollution source.

3.2. Anthropogenic Changes in Tree-Ring Series Variance

As mentioned in section 2 of this article, for the investigation of anthropogenic changes in tree-ring series variance in the polluted environment, the investigated tree-ring series were split into two parts and analysed separately. The first part occupies the beginning of time series till 1965, when 'Achema' started producing fertilizers and environmental situation was changed considerably. Second part of time series (from 1965) was considered as anthropogenic transformed. Taking into

TABLE I

Comparison of tree-ring series variance prior to the construction of the plant and following it

State of stand	No. of stand	L, km	Tree-ring series variance up to 1965	after 1965	F-test for homogeneity of variances	p of F-test
Damaged stands	1	2.6	259.0	1335.5	5.16	0.000001
	2	3.2	101.6	248.4	2.45	0.008315
	3	6.0	190.8	475.7	2.49	0.010805
	4	6.5	116.0	381.6	3.29	0.001308
	5	11.4	147.5	713.1	4.83	0.000024
	6	10.9	77.5	435.7	5.63	0.000004
	7	20.6	171.2	244.2	1.43	0.315450
	8	21.3	248.8	502.9	2.02	0.045988
Control stands	1		167.8	170.4	1.22	0.541651
	2		154.2	188.9	1.02	0.955723
	3		267.5	167.4	1.60	0.173078

account, that age of investigated Pine stands is 80 – 90 years, two approximately equal parts of time series were obtained for each of them. Statistical significance of differences between the variance of these two parts of tree-ring indexes series without the influence of autocorrelation was assessed according to F criteria.

Most of standardized increment series $\{z_t\}$ are rather strongly autocorrelated. Their partial autocorrelation function has shown that it is possible to consider them as autoregression process (ARIMA (1,0,0)) of the first rank:

$$z_t - m = p(z_{t-1} - m) + e_t, \tag{2}$$

where m – the mean of indexes series, $\{e_t\}$ – series of uncorrelated random values with 0 mean and identical variance.

Series $\{e_t\}$ are a series of approximated increment indexes that are devoid of the influence of autocorrelation.

Investigation of different authors has shown, that age of trees also has some influence on the variance of tree-ring series. The decreasing of tree-ring variances was estimated depending on increasing of tree age (Fritts, 1976; Briffa *et al.*, 1996; Schweingruber, 1996; Lovelius, 1997). For the comparison, tree-ring series of the control stands were analysed in the same manner. The results of this analysis are presented in Table I.

It can be seen from presented results (Table I), that the variance of tree-ring series increased significantly ($p < 0.05$) in the polluted environment, with exception of one stand most distant from the pollution source. As seen from Figure 3,

more intensive fluctuations of destabilized systems continue despite very essential reduction of anthropogenic impact.

Differences of variance for the same periods in the c ontrol stands are relatively slight and statistically insignificant (Table I).

3.3. Anthropogenic Changes in the Tree-Ring Relations with Climatic Factors

One of the presumptions was made at the beginning of this article – not only the intensity of the growth (tree-ring width) and the intensity of temporal fluctuations are changed, but also the relations of tree growth with different climatic factors should be transformed in the polluted environment. As it was noticed by Cook (1987b), breakdown in the relationship between tree rings and climate could be considered as an impact of a new environmental stressor. The decrease in the correlation between tree rings and climate in the polluted environment was the most expected result of this investigation.

Comparison of tree-ring relations with climate for the period before 'Achema' started, and for the period after that was made in a similar way, as well as anthropogenic changes of tree-ring series variance were investigated – tree-ring series were split into two parts (till 1965 and from 1965) and their relations with climate were analysed separately.

Taking into account, that the relations of tree-rings with different climatic factors are rather weak and the coefficient of correlation does not usually exceed 0.3–0.4 (Bitvinskas, 1989; Juknys, Vencloviene, 1998), interpretation of their anthropogenic changes is rather complicated. Nevertheless, the results obtained during this investigation were rather unexpected.

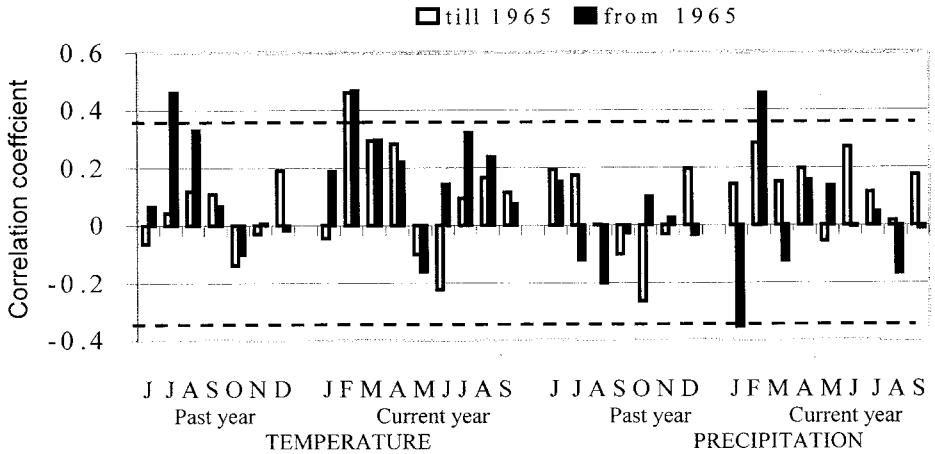


Figure 6. Comparison of tree-ring relations with climatic factors (--- significance level ($p<0.05$).

First of all, the increase in the tree-ring dependence on climate under polluted environment is rather typical of all investigated tree-ring series of damaged Pine stands.

Most essential and in some cases statistically significant increase was found for the tree-ring correlation with temperatures of summer months (July, August). Especially evident is stronger correlation between the tree-ring and climatic conditions – summer and winter temperatures of the last year (Figure 6).

On the other hand, the correlation between the tree-rings and temperatures of late winter and early spring is usually strongest for both investigated periods (before and after 'Achema' was run). However, some strengthening of these relationships in the polluted environment is rather typical as well.

The presented results load to a general conclusion – reaction of trees to the impact of climatic factors (temperature, precipitation) has changed in the polluted environment and the sensitivity of trees has increased.

4. Conclusions

For the quantitative assessment of anthropogenic changes in the biological indicators the problem of norm (normal annual increment in the case of tree-ring analysis) is very important. Taking into account quasiperiodical fluctuations of biological and environmental parameters, the detection of an anthropogenic signal is a rather difficult problem.

Multiple climate response models are one of the most appropriate tools for the prediction of normal annual increment, as a basis for the assessment of its anthropogenic changes in the polluted environment. According to our investigations, usually 4–6 climatic factors prove to be statistically significant and 35–70% of tree-ring series variance is attributed to the climatic factors included into multiple climate response models. The temperatures of late winter (February), early spring March, April) and temperatures of late summer (August) affect Pine growth most strongly in our climatic conditions. Temperatures of past autumn (October) are included into climate response models rather frequently. The impact of precipitation is by far less essential in our latitudes. The precipitation of late winter (February) and summer (June, July) has statistically significant impact on the growth of some investigated Pine stands ($p < 0.05$).

Resolving capacity of climate response models is decreasing with the increase of prediction period. In the case of prediction for a period of ten years, the standard error does not usually exceed 10%, and in the case of a longer (20–30 years) prediction, anthropogenic changes not less than 15% can be assessed as statistically reliable.

Three different periods of anthropogenic transformations of tree growth were singled out on the basis of tree-ring analysis – fertilization period, depression period and recovery period. Since 1965, when 'Achema' started, emitted nitrogen

compounds have had a positive impact and annual tree increment has increased as compared with the normal growth. However, several years later the general impact of increased emissions became negative and growth depression period started. The exclusively cold winter of 1978/79 was an additional unfavourable external factor in this case. Recovery of damaged stands has started from the mid-1980s, as a consequence of essential reduction of environmental pollution and annual increment has reached a normal level or even exceeded it.

Variance of tree-ring series has increased significantly in the polluted environment. More intensive fluctuations of once destabilized system continue despite an essential reduction of anthropogenic impact.

Tree-ring relations with climate have basically changed in the polluted environment. The increase in tree-ring dependence on climate in the polluted environment is quite typical of all investigated tree-ring series of damaged Pine stands. Most essential and in some cases statistically significant ($p < 0.05$) increase was found for the tree-ring correlation with temperatures of summer months (July, August). Especially evident is stronger correlation between tree-ring and climatic conditions of the past year – summer and winter temperatures. The correlation of tree-rings with temperatures of late winter and early spring is usually strongest for both investigated periods (before and after 'Achema' was run). However, some strengthening of these correlations in the polluted environment is rather typical as well. Such a general conclusion can be made on the basis of obtained results – sensitivity of trees to the impact of natural external factors has increased in the polluted environment.

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References

Armolaitis, K.: 1998, 'Nitrogen pollution on the local scale in Lithuania: vitality of forest ecosystems', *Environ. Pollut.* **102**, 55–60.

Bauer, F.: 1982, 'Kommt es Forstlich zur Katastrophe?', *Allgemeine Forstzeitschrift* **37**, 865–867.

Bitvinskas, T.: 1989, 'Prognosis of Tree Growth by Cycles of Solar Activity', in: E. Cook and L. Kairiukštis (eds), *Methods of Dendrochronology. Applications in the Environmental Sciences*, Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 332–337.

Braker, O. U. and Gaggen, S. Z.: 1987, 'Tree Ring Analysis in the Swiss Forest Decline Study of 1984', in: L. Kairiukštis, S. Nilsson and A. Straszak (eds), *Forest Decline and Reproduction: Regional and Global Consequences*, Laxenburg, Austria, pp. 124–129.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., Karlén, W. and Shiyatov, G.: 1996, 'Tree-ring Variables as Proxy-Climate Indicators: Problems with Low Frequency Signals', *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, Proceedings of the NATO advanced research workshop held at Il Ciocco, Lucca, Italy, October 3–7, 1994.

Cook, E. R.: 1987a, 'The decomposition of tree ring series for environmental studies', *Tree-Ring Bull.* **47**, 37–59.

Cook, E. R.: 1987b, 'The Use of Climatic Response Models of Tree Rings in the Analysis and Prediction of Forest Decline', in: L. Kairiukštis, Z. Bednarz and E. Feliksic (eds), *Methods of Dendrochronology-1*, Proceedings of the Task Force Meeting on Methodology of Dendrochronology East/West Approaches, 2–6 June, 1986, Krakow, Poland, pp. 269-276.

Draper, N. R. and Smith, H.: 1986, *Applied Regression Analysis*, John Wiley & Sons, New York-London, 439 p.

Eckstein, D.: 1985, 'On the Application of Dendrochronology for the Evaluation of Forest Damage', in: P. Schmid-Haas (eds), *Inventorying and Monitoring Endangered Forests, Materials of IUFRO conference*, August 19–24, 1985, Zurich, Switzerland, pp. 287–290.

Eckstein, D.: 1989, 'Qualitative Assessment of Past Environmental Changes', in: E. Cook and L. Kairiukštis (eds), *Methods of Dendrochronology. Applications in the Environmental Sciences*, Kluwer Academic Publishers, Dordrecht, pp. 220–223.

Fritts, H. C.: 1976, *Tree Rings and Climate*, London: Academic Press, 567 p.

Hosker, R. P. and Lindber, S. E.: 1982, 'Review: Atmospheric deposition and plant assimilation of gases and particles', *Atmos. Environ.* **16,** 889–910.

Innes, L. J. and Cook, E. R.: 1989, 'Tree-ring analysis as an aid to evaluating the affects of pollution on tree growth', *Can. J. For. Res.* **19**, 1174–1189.

Jones, P. D.: 1989, 'Possible Future Environmental Change', in: E. Cook and L. Kairiukštis (eds), *Methods of Dendrochronology. Applications in the Environmental Sciences*, Kluwer Academic Publishers, Dordrecht, pp. 337–340.

Juknys, R.: 1994, 'Dendrochronological Data Applications at the Forest Monitoring System', in: J. Solon, E. Roo-Zielinska and A. Bytnerowicz (eds), *Climate and Atmospheric Deposition Studies in Forests, Conference Papers*, 1993, IGSO PAS, Warsaw, Poland, pp. 245–254.

Juknys, R.: 1995: 'Trends of Lithuanian environment during transitional period', *Env. Res. Engineer. Manage.* **1**, 15–24.

Juknys, R. and Jancys, E.: 1998, 'Dendrochronology for Environmental Impact Assessment', in: V. Stravinskiene and R. Juknys (eds), *Dendrochronology and Environmental Trends*, Proceedings of the International Conference 'Eurodendro- 98', Kaunas, Lithuania, pp. 169–177.

Juknys, R. and Vencloviene, J.: 1998, 'Quantitative Analysis of Tree-ring Series', in: V. Stravinskiene and R. Juknys (eds), *Dendrochronology and Environmental Trends*, Proceedings of the International Conference 'Eurodendro-98', Kaunas, Lithuania, pp. 237–249.

Kairiukštis, L., Grigaliunas, J., Skuodiene, L. and Stravinskiene, V.: 1987, 'Physiological and Dendrochronological Indications of Forest Decline and Their Application for Monitoring', in: L. Kairiukštis, S. Nilsson and A. Straszak (eds), *Forest Decline and Reproduction: Regional and Global Consequences*, Laxenburg, Austria, pp. 151–169.

Kairiukštis, L. and Stravinskiene, V.: 1992, 'Application of dendrochronology in regional monitoring of forest decline', Lund University, Department of Quaternary Geology, Lund, *Tree Rings Environ.* **34**, 159–161.

Knabe, W.: 1985, 'Das Waldsterben aus Immisionsokologischer Sicht', *Geogr. Rundschau* **35**, 249–256.

Lovelius, N. V.: 1997, *Dendroindication of Natural Processes and Anthropogenic Influences*, St. Petersburg, 320 p.

Mehne-Jakobs, B. M.: 1990, 'Untersuchungen zur Überprufung der Epidemiehzpothese als Erklärungsansatz zu den 'neuartiger' Waldschäden', *Allgemeine Forst- Jagdzeitung* **161**(12), 231–239.

Ozolincius, R. and Stakenas, V.: 1999, 'Regional Forest Monitoring', *Monitoring of Forest Ecosystems in Lithuania*, Lutute, Kaunas, pp. 82–106.

Philips, S. O., Skelly, J. M. and Burkhart, H. E.: 1977, 'White pine growth retardation's by fluctuating air pollutant levels: interaction of rainfall, age and symptom expression', *Phytopatthology* **67**, 721–725.

Pollanschutz, J.: 1987, 'Effects of Air Pollutants on Forest Growth', in: L. Kairiukštis, S. Nilsson and A. Straszak (eds), *Forest Decline and Reproduction: Regional and Global Consequences*, Laxenburg, Austria, pp. 125–129.

Schulce, E. D.: 1989, 'Air pollution and forest decline in a spruce *(Picea abies)* forest', *Science* **244**, 776–783.

Schweingruber, F. H.: 1989, 'Dendroecological Information in Pointer Years and Abrupt Growth Changes', in: E. Cook and L. Kairiukštis (eds), *Methods of Dendrochronology. Applications in the Environmental Sciences*, Kluwer Academic Publishers, Dordrecht, pp. 277–283.

Schweingruber, F. H.: 1996, *Tree Rings and Environment Dendroecology*, Swiss Federal Institute for Forest, Snow and Landscape Research: Paul Haupt Publishers. Berne-Stuttgart-Vienna, 609 p.

Stravinskiene, V.: 1995, 'Impact of local environmental pollution on increment of conifers', *Forestry*(Kaunas). **36**, 82–99 (in Lithuanian, summary in English).

Vinš, B. and Mrkva, P.: 1973, 'The diameter increment losses of pine stands as a result of injurious emissions', *Acta Univ. Agricult.*(Brno). **42**, 25–46.

Žukauskas, A., Jaskelevičius, B., Stumbras, A. and Žiugžda, V.: 1996, 'Historical Aspects and Geographical Distribution of Pollutants in Lithuania', *Ecological Sustainability of Lithuania (ECOSLIT)*, Vilnius, pp. 29-33.