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Scots pine (*Pinus sylvestris* L.) growth and condition in a polluted environment: from decline to recovery

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"Capsule": *A lag period of several years occurred before tree recovery began.*

Abstract

The results of long-term investigations of Scots pine (*Pinus sylvestris* L.) growth and condition in the impact zone of one of the biggest air pollution sources in Lithuania—mineral fertilizers plant "Achema" are presented. The main attention is laid to the recovery of damaged stands since annual emissions to air were reduced essentially. The investigations indicated, that the recovery of tree increment was mostly caused by distinct reduction of emissions of nitrogen and sulphur oxides and dust of mineral fertilizers. Despite reduced pollution, crown defoliation of investigated stands has continued to increase for a certain period. After the crown recovery of damaged stands has started, the recovery of most damaged survived trees was most intensive and convergence of defoliated to a different extend stands and trees is characteristic feature of this period. No defoliation threshold has been determined beyond of which recovery of trees would be impossible. Recovery of more than a quarter of damaged trees was registered even in the case of 90% of defoliation. Recovery of dominant trees occurs to be faster of that for suppressed trees within the same level of defoliation. The impact of stand density on the crown recovery rate is negative, the higher density (more intensive competition), the slower recovery of damaged trees. The dependence of growth rate on defoliation was found to be of logistic character: while crown defoliation consists up to 25–30%, tree increment losses are rather inconsiderable, further increase of defoliation leads to the essentially higher increment losses, however having achieved 65–70% defoliation, further increase of defoliation does not result such intensive decrease of radial increment.

Keywords: Air pollution; Defoliation; Radial increment; Decline and recovery

1. Introduction

Forest damages in the polluted environment have already been recorded in the middle of the nineteenth century (Donaubauer, 1980). However, it was considered to be a purely local problem up to 1980. The first signs of forest damage on a regional scale were noticed in Germany at the very beginning of 1980s (Knabe, 1981; Bauer, 1982) and very soon similar messages were published in the other countries of Central and Western Europe (Karl, 1986; Krause et al., 1986, etc.). Forest decline on the vast areas of Europe and the North America has become one of the most serious ecological problems. The regional damage of forests in Lithuania has been observed since the middle of 1980s (Ozolincius and Stakenas, 1999).

At present, there are plenty of hypotheses specifying the main reasons of regional forest decline. Unfavourable climatic conditions, invasion of forest pests, diseases and errors of forest management (plantations with monocultures, intensive felling, fertilization, etc.) were often mentioned along with environmental pollution (Auclair et al., 1992; Houston, 1992; Innes, 1993, etc.). In the opinion of most scientists, forest decline is caused by a complex of natural and anthropogenic stressors, however the main reason of this phenomenon undoubtedly is environmental pollution, while the other factors only strengthen the impact of pollutants. Long-range

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transboundary pollution and environmental acidification are considered as the main factors, resulting forest decline on a regional scale (Mehne-Jacobs, 1990; Landmann and Bonneau, 1995; Miller et al., 1996, etc.).

Reduction of air emissions, as a result of international efforts, was started in the Western Europe in the middle of 1980s. After the collapse of the Soviet block, along with transitional economy decline, the essential reduction of air emissions took place in the East European countries as well at the beginning of 1990s. The emissions of sulphur in Lithuania were reduced more than three times during the past 10 years. The emissions of nutrient nitrogen decreased not so essentially—about 30% (Sopauskiene, 1996; Juknys, 2000). Lower emissions caused improvement of air quality and reduction of acid deposition. Total (dry and wet) annual deposition of sulphur in Lithuania constituted about 25 kg per hectare at the beginning of 1990s and in recent years usually does not exceed 7–10 kg; deposition of nitrogen was reduced from 15 kg up to 10–12 kg per hectare (Sopauskiene and Jasineviciene, 1997). Air pollution in the surroundings of the biggest industrial enterprises decreased even more than on regional scale (Armolaitis, 1998).

Growth and condition of damaged forests started to improve both locally and on the regional scale as the result of these positive environmental changes (Hendriks et al., 1997; Klap et al., 1997; De Vries et al., 1997; Ozolincius and Stakenas, 1999, etc.). Taking into account that recovery of damaged forests under reduced environmental pollution is comparatively new and little investigated process, the main aim of presented article was to investigate recovery possibilities of differently damaged Scots pine forests.

2. Materials and methods

Scots pine forests in the surroundings of one of the biggest air pollution sources in Lithuania the mineral fertilizer plant "Achema" were chosen for the study. Taking into account that emissions of this plant were reduced dramatically during the past 15 years, a rapid recovery of surrounding forests has started. As far as the composition of Achema emissions is rather common (sulphur, nitrogen, carbon oxides and dust), the obtained results to a certain extent will be valuable estimating and forecasting possibilities of forest recovery on the regional scale as well.

Achema (former "Azotas") was founded in the central part of Lithuania (55°05′ latitude, 24°20′ longitude), at the confluence of the Rivers Neris and Sventoji in 1965. Production of the plant and its emissions permanently grew up till 1978, when most polluting Nitrofosca department was run. Nitrogen fertilizers, produced by fixing nitrogen from air, are the basic Achema production. This process requires a particularly large amount of energy, so sulphur, nitrogen and carbon oxides comprise the main part of emissions as a result of burning organic fuel. A rather large quantity of ammonia and dust of mineral fertilizers were emitted into the air while producing these fertilizers (Table 1). Apatites from Cola peninsula were imported as a raw material for nitrophoska production and small quantities of heavy metals (Zn, Cu, Mn, Cr, Ni, Cd, etc.) were detected in emissions as well.

The first signs of local forest damages were noticed in 1972, but this problem became extremely acute since 1979, when after particularly cold winter apparent tree crown defoliation in the direction of prevailing winds was recorded up to 10–12 km, and at the distance of 2–3 km from Achema coniferous forests completely died. Despite essential reduction of emissions at the beginning of 1980s, when the different pollution mitigation measures were implemented in Achema, damaged forests in the direction of prevailing winds expanded up to 20–25 km at the end of 1980s. The additional decrease of emissions was recorded since 1989, when the most polluting department, producing nitrophoska, was closed after a dangerous accident. Recently annual emissions of Achema do not exceed 5000–7000 tons, i.e. several times lower than in 1980 (Table 1).

Within the significant decrease of emissions, deposition of acid compounds has decreased as well. In the mid of 1980s total (wet and dry) annual deposition of sulphur at the distance of 1–2 km from the factory comprised about 50 kg and at a distance of 20–22 km—over 30 kg, currently it was reduced up to 15 and 9 kg,

Table 1
Annual emissions of Achema plant in 1980–2000

Year	Emission, tons					
	SO_2	NO_X	CO	NH4	Dust	Total
1980	3901.219	4148.45	8548.393	3621.546	12995.29	33214.90
1981	4630.000	3862.00	9874.000	3734.000	13860.00	35960.00
1982	4078.554	3895.74	10541.140	3632.586	11475.87	33623.89
1983	3698.707	3594.51	9711.052	3033.941	8098.07	28136.28
1984	3311.930	2776.96	9927.734	2590.949	6327.77	24935.34
1985	2635.278	2885.57	9456.281	2425.752	4476.72	21879.60
1986	2975.146	2730.30	10290.750	2559.082	3237.73	21793.01
1987	2416.107	2357.50	9682.346	2495.464	1705.33	18656.75
1988	1990.893	2205.56	8355.524	1551.339	629.27	14732.59
1989	1295.471	1824.08	6608.158	3657.579	271.11	13656.40
1990	716.439	908.29	6142.778	2248.638	304.85	10321.00
1991	450.437	1133.33	7318.010	2249.045	351.31	11502.13
1992	438.069	689.95	6903.604	2054.587	246.22	10332.43
1993	629.723	243.46	3923.684	678.304	212.12	5687.29
1994	378.889	359.10	3012.690	719.677	273.67	4744.03
1995	369.980	324.05	3474.710	1286.911	291.94	5747.59
1996	24.169	121.87	3450.397	645.110	285.00	4526.55
1997	541.425	388.78	3509.681	381.721	265.30	5086.91
1998	68.217	389.90	5703.550	256.974	202.70	6621.34
1999	83.000	380.71	5362.167	196.512	300.95	6323.34
2000	8.235	415.69	5769.850	285.565	323.38	6802.72

respectively. Deposition of oxidized and reduced nitrogen decreased several times as well and at the distance of 20–22 km from the factory it constitutes 15–17 kg per hectare annually (Armolaitis, 1998).

Permanent investigations of Scots pine forests in surroundings of Achema were started at the beginning of 1980s and have continued for almost 20 years. A three-stage sampling pattern was used for the collection of field materials: (1) sampling of research stands; (2) sampling of circular plots within each research stand; (3) sampling of trees for more detailed measurements of tree stem and crown indicators and tree ring analysis. Twelve circular sample plots were established in each research stand. Sample plots were distributed in a systematic way—according to a grid. The place of the first sample plot was chosen randomly. The area of circular sampling plots was determined to contain on average 15–20 trees. The tree stem diameter was permanently measured and crown defoliation estimated for all sample trees every 3–5 years. European forest monitoring methodology was used for the estimation of tree condition (crown defoliation) and five defoliation classes were distinguished: class 0 (conditionally healthy trees)—defoliation up to 10%; class 1 (slightly damaged trees)—defoliation 11–25%; class 2 (moderately damaged trees)—defoliation 26–60%; class 3 (severely damaged trees)—defoliation 61–99%; class 4 (crown defoliation equals 100%)—dead trees (UNECE, 1994).

During the third sampling stage three closest to the centre of sampling plot trees were sampled, the main stem and crown parameters (diameter, height) were measured and wood samples for tree-ring (annual radial increment) analysis by the special borer were taken.

Data of eight semi-mature even-aged (80–90 years old) Scots pine stands, situated in different distances from the pollution source (3–22 km) in the direction of prevailing winds were used for this study. Changes of radial tree increment (width of annual tree rings) and crown defoliation under reduced air pollution as well as influence of defoliation to the tree growth were investigated.

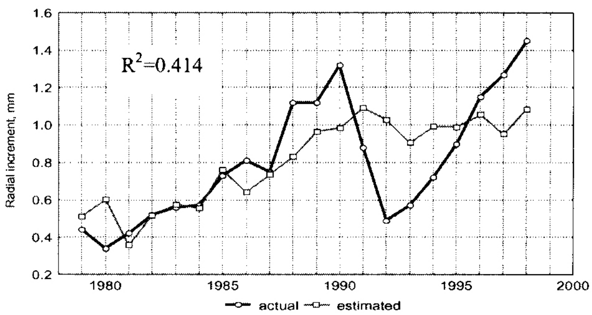
3. Results and discussion

The multiple regression analysis on dependence of annual radial increment on the amount of emissions of different pollutants have been performed while investigating the impact of reduced air pollution on tree growth. It was obtained that recovery of annual radial increment of trees was mostly caused by the reduced emissions of nitrogen and sulphur oxides, and dust of mineral fertilizers. Actual and estimated (according to the regression model) values of annual radial increment of Scots pine stand situated most closely to the pollution source (3.2 km) are presented in Fig. 1. As is seen, the regression model including sulphur and nitrogen oxides as the main factors reflects the general increase of tree radial increment with the reduction of air pollution rather well and specifies more than 40% of increment dispersion ($R^2=0.414$). The dependence of tree increment on emissions with the increase of distance from the pollution source has decreased and for the most distant stand (over 20 km) it became statistically insignificant ($P>0.05$).

Changes of tree increment depend not only on air pollution, but on climatic factors as well (Fritts, 1976; Cook, 1987; Stravinskiene, 1995, 2002, etc.). Our earlier investigations have showed that temperatures at the end of winter and spring as well as precipitation at the end of winter and summer influences Scots pine growth in Lithuanian geographic latitudes most essentially (Juknys et al., 2002). Our aim to approximate the changes of radial increment more exactly, values of climatic factors were included into the multiple regression models additionally. Analysis has showed that temporal reduction of tree increment during 1992–1995 was mostly caused by particularly dry summers of 1992 and 1994. As it is seen from Fig. 2, precipitation in June is included into all regression models.

Actual and estimated according to multiple regression models values of annual radial increment are presented in Fig. 2. Having compared the radial increment data of the stand closest to the pollution source (Figs. 1 and 2), it is seen that approximation of increment recovery gets far better ($R^2=0.669$) when additionally including climatic factors. Approximation level (R^2) decreases with the increase of distance to the pollution source, however, with exception of the most remote stand, such a type of models explains more than a half of increment dispersion ($R^2>0.5$) and specifies obvious increment recovery while air pollution decreases.

General trends of crown defoliation during 1982–2000 are presented in Fig. 3. As seen, at the beginning of investigation crown defoliation of the closest to the pollution source and mostly damaged stand was more than twice that of the most remote stand. However later



$$W_t = 1.042 - 0.0277\,SO_2 + 0.154\,NO_x$$

Fig. 1. Actual and estimated values of radial increment (regression model based on data of emissions).

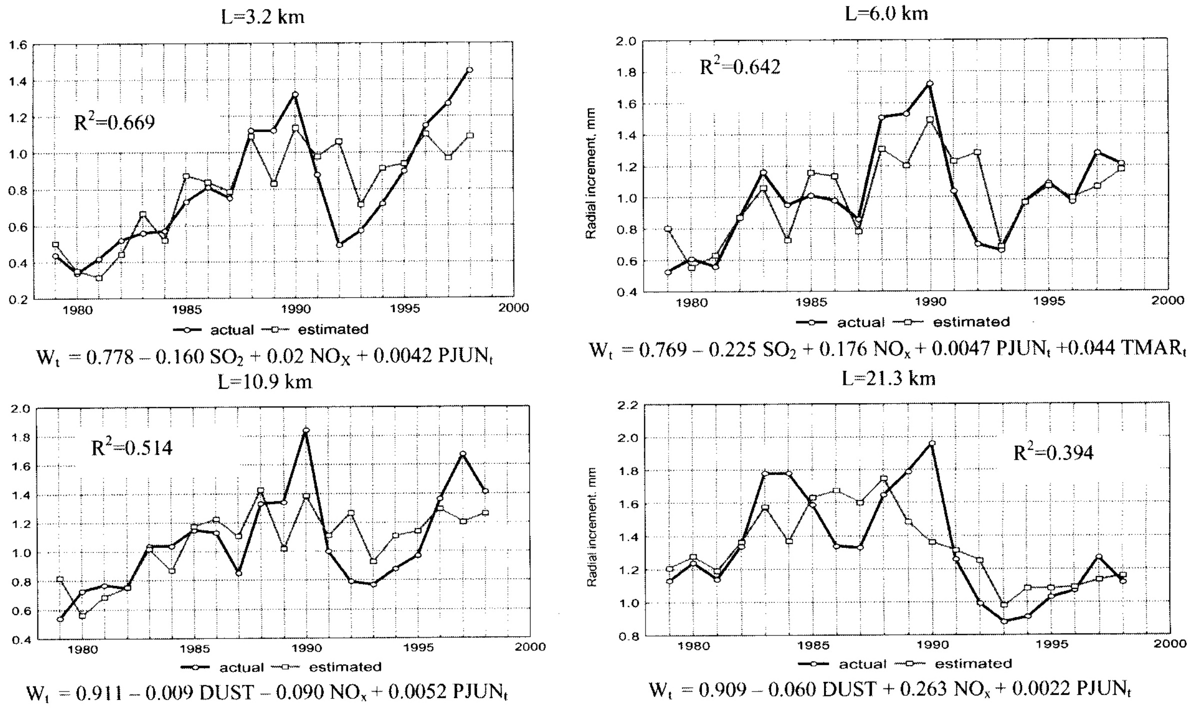


Fig. 2. Actual and estimated values of radial increment (regression model based on data of emissions and climatic factors).

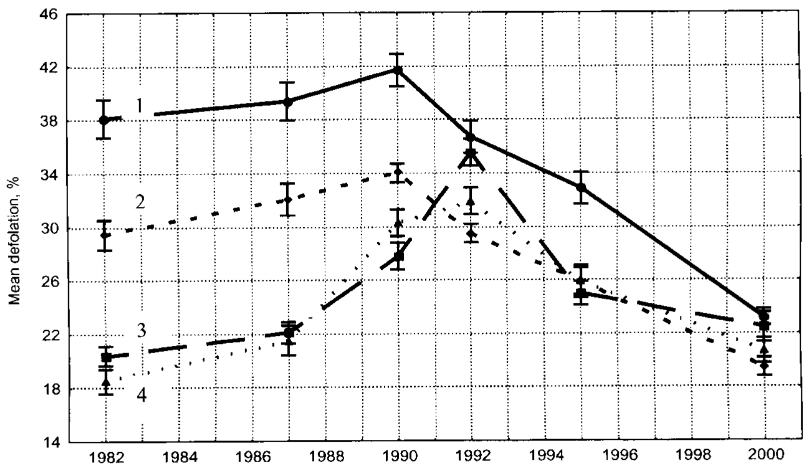


Fig. 3. Changes of mean defoliation at different distances (L) from pollution source: 1—L = 3.2 km; 2—L = 6 km; 3—L = 10.9 km; 4—L = 21.3 km.

these differences started to decrease and convergence of differently damaged stands began. Differences in an average defoliation of Scots pine stands situated on the different distances from pollution source did not exceeded 4% and in most cases were statistically insignificant ($P > 0.05$) in 2000. Currently average defoliation of investigated stands only slightly exceeds an average defoliation of Scots pine in non-industrial areas of Lithuania (Sepetiene and Bartkevicius, 1996; Ozolincius and Stakenas, 1999). It is important to notice that despite the reduction in emissions, defoliation of damaged stands still increased until 1990–1992. Lag of several years in positive changes of tree crown condition in the reduced environmental pollution can be noticed on regional level as well. As was mentioned earlier, emissions and deposition of acid compounds in Europe started to decrease rather considerably since the middle of 1980s, however a more intense decrease of tree crown defoliation in many countries including Lithuania, was registered only from 1994 to 1995 (Klap et al., 1997; Erisman and Vries, 1999; Ozolincius and Stakenas, 1999).

More detailed analysis of tree crown defoliation changes within crown recovery period (1990–2000) in the surroundings of Achema is presented further. Probabilities of tree transition from current class of defoliation to other classes were evaluated. In this case, defoliation class is considered as the state of the tree at the beginning of the period. Following the changes of tree defoliation, their state (defoliation class) has changed from i ($i=0, 1, 2, 3$) to j ($j=0, 1, 2, 3, 4$). Description of defoliation classes is presented in the methodics. Probabilities of tree transition to other defoliation classes P_{ij} are presented in the shape of transition matrixes (P_{ij}), $\Sigma P_i = 1$. Empirical P_{ij} values were approximated by exponent of squared polynomial in respect to i and j:

$$P_{ij} = \exp(5.54 - 1.59 \times i - 0.705 \times i \times j - 0.46 \times j \times j) / \left(\sum_{j=1}^{5} \exp(5.54 - 1.59 \times i + 0.705 \times i \times j - 0.46 \times j \times j)\right), \quad R^2 = 0.591 \tag{1}$$

Approximated probabilities of tree transition to other defoliation classes (in%) are presented in the Table 2. Each row of the table presents a part of the trees that moved to other defoliation classes or remained in the same class during the recovery period.

As seen from Table 2, the state of mostly damaged trees has changed most rapidly. Only 25% of severely damaged trees (class 3) remained in the same class and two thirds improved their state. Almost one third of severely damaged trees moved to class 1 (slightly damaged trees) or even class 0 (conditionally healthy ones). Less than one third of moderately damaged trees (class 2) remained in the same class and more than 55% improved their state. During this period the most stable occurred to be the condition of relatively healthy trees (class 0), however more than one third of trees from this class moved to lower classes.

It should be noted that while carrying out investigations of damaged forests in the 1980s, the opinion was that heavily damaged stands and trees had no possibility to improve their state even in the case of essential reduction in environmental pollution, and this process is irreversible (Dabrovska-Prott, 1986). However, as it is seen from data presented in Table 2, the Scots pine trees occurred to be much more resistant than expected and with the decrease in environmental pollution, the condition of more than half of the severely damaged trees (class 3) improved. Taking into account that from 1990 instead of rather rough classes, defoliation is evaluated within 5% of accuracy, attempts to determine a threshold of crown damage, beyond which recovery of trees becomes impossible was made. Analysis of data has showed that even in the case of 90% defoliation, recovery of more than a quarter of damaged trees was registered. Consequently, instead of the threshold of irreversible damages, we should consider the higher or lower probability of tree recovery in reduced environmental pollution.

Parameters of trees and stands, affecting most strongly the rate of crown recovery in the reduced environmental pollution were investigated further. A multidimensional regression model was constructed on the basis of collected field data:

$$R = -0.76 + 0.068 \times F - 0.00074 \times N + 0.000034 \times D \times F - 0.028 \times F/(1 + 16 \times \exp(-0.05 \times F)); \quad R^2 = 0.382, \tag{2}$$

where R, annual rate of crown recovery, %; F, crown defoliation, %; D, stem diameter, cm; N, the stand density (number of trees per hectare).

A graphical view of crown recovery rate dependence on tree crown defoliation and stem diameter within mean stand density is presented in Fig. 4. As is seen, more intensive recovery is characteristic for heavier defoliated trees. We have already seen from Table 2 that

Table 2
Probability (%) of tree transition from one defoliation class to another during crown recovery period (1990–2000)

Initial defoliation class	Final defoliation class				
	0	1	2	3	4
0	61.7	31.9	6.4	0.0	0.0
1	39.6	40.8	16.9	2.7	0.0
2	18.3	38.1	31.7	10.5	1.4
3	5.4	23.0	38.8	25.9	6.9

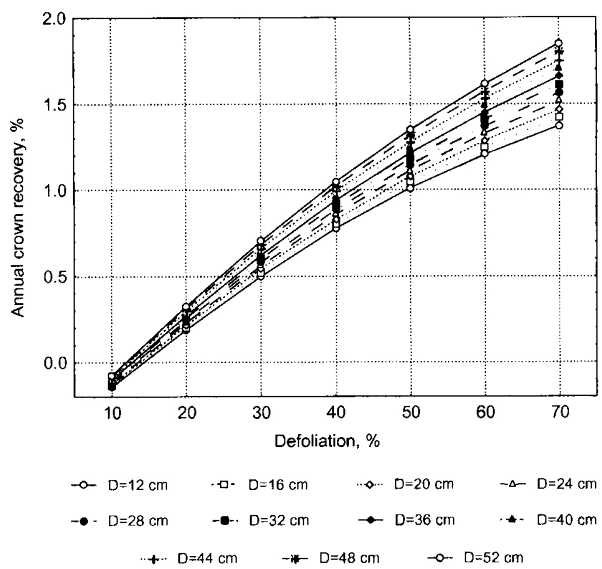


Fig. 4. Dependence of annual crown recovery rate on crown defoliation and stem diameter.

during the recovery period the most intensive changes took place in the most damaged groups of trees (defoliation class 2 and 3).

It is also seen from data presented in Fig. 4 that crown recovery rate of the largest (dominant) trees occurs faster than for suppressed trees. As seen from the presented multiple regression model [Eq. (2)], the impact of stand density on the rate of crown recovery is negative—the higher density (more intensive competition), the slower recovery of damaged trees. These regularities might be partly explained by pine heliophilousness (Ellenberg et al., 1991). Dominant and thinly growing trees receive more light that stimulate a more intensive process of photosynthesis and define more fast recovery. Whereas the recovery process of suppressed trees is slower due to shortage of light.

The impact of crown defoliation on tree growth tends to be one of the target questions while investigating the state and growth of damaged stands. The focus of most frequent investigations in this area is the relationship of crown defoliation with radial increment (width of annual rings). There is no unanimous opinion on crown defoliation impact to the tree increment. Some of the researchers did not find a statistically significant relationship between crown defoliation and tree increment (Kohler and Stratman, 1986); other authors found that trees with needle losses up to 25% have insignificant increment losses (Schweingruber, 1985; Soderberg, 1991), while rapid increment decrease starts, when crown defoliation exceeds 40% (Petras et al., 1993) or even 50% (Frantz et al., 1986).

A rather sophisticated pattern of tree increment dependence from crown defoliation was pointed out in the investigation of R. Ozolincius (1996). He has made a conclusion that under the increase of crown defoliation from 35 to 60% tree increment decreases most rapidly. While with defoliation increase from 0 to 35% and from 60 to 85% radial increment almost does not change. The investigations carried out by H. Kramer (1986) have indicated that analysing the impact of crown defoliation on tree increment, quantitative crown parameters should be taken into consideration as well. Crown surface area and crown volume are usually considered the main quantitative crown indicators in such a type of investigations. Analysis of our experimental data has showed that stem diameter correlates with crown parameters very closely and correlation in all the cases was statistically significant ($P<0.05$). The following coefficients of correlation were obtained—with crown diameter of 0.525–0.825; with crown length of 0.506–0.823; with crown volume of 0.712–0.945. In all the cases, while approaching to the pollution source and increasing damages, weakening of relationships was recorded.

Taking into account the very strong correlation between stem diameter and crown volume, the dependence of radial increment on crown defoliation and stem diameter was analysed further. In this case crown defoliation was considered as qualitative crown indicator and stem diameter—as an indicator reflecting quantitative parameters of trees. Following the multiple regression model was elaborated:

$$\begin{aligned} \mathrm{Zr} &= 0.528 + 0.0043 \times D - 0.0037 \\ &\quad \times D/(1 + 16 \times \exp(-0.05 \times F)); \qquad (3) \\ (R^2 &= 0.413) \end{aligned}$$

where Zr, annual radial increment, mm; D, stem diameter, cm; F, crown defoliation, %.

The dependence of radial increment on crown defoliation and stem diameter approximated according to the elaborated model is presented in Fig. 5. As seen, the dependence of radial increment on crown defoliation is expressed by logistic curve. At first, while defoliation increases until 25–30%, radial increment decreases relatively slowly. As mentioned earlier, other researchers pointed out this regularity as well (Schweingruber, 1985; Soderberg, 1991). Further increase of defoliation leads to the essentially higher increment losses, however having achieved 65–70% defoliation, the increase of defoliation does not result such fast decrease of radial increment. These results correspond rather well with the conclusions of Ozolincius (1996) that were mentioned earlier, however different intervals of defoliation are not strictly delimited.

Results of multiple regression analysis (Fig. 5) showed that the impact of crown defoliation on tree increment markedly depends on quantitative parameters of the trees. The impact of defoliation on increment of thin,

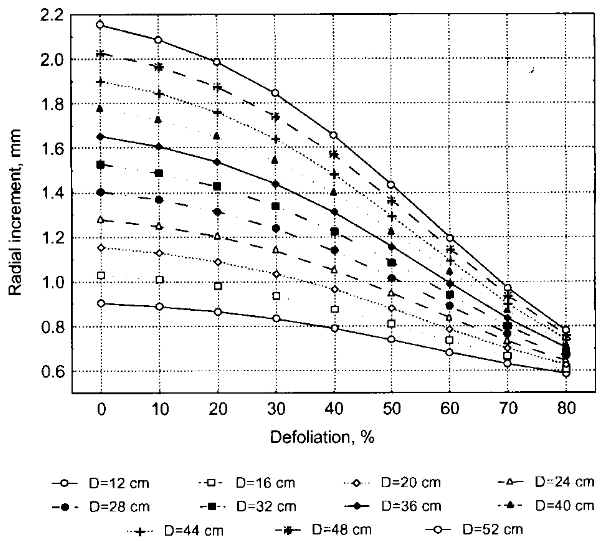


Fig. 5. Dependence of Scots pine (*Pinus sylvestris* L.) radial increment on crown defoliation at different stem diameter.

suppressed trees is relatively much weaker than for thick ones. While defoliation of large trees increases from 5 to 75%, their radial increment decreases 3–4 times, whereas the increment of thin trees in the same defoliation interval decreases about 1.5–2 times.

4. Conclusions

Reduction in emissions from a mineral fertilizers plant has caused a considerable recovery of surrounding Scots pine forests. The results of this investigation have indicated that recovery of radial increment of trees was mainly caused by the reduced emissions of nitrogen and sulphur oxides and dust of mineral fertilizers. The dependence of tree increment on emissions has decreased with the increase of distance from the pollution source and for most distant stand (over 20 km) became statistically insignificant. It is necessary to take into account the impact of natural environment factors while analysing growth of the forests in the polluted environment, because the changes in tree increment are influenced not only by air pollution but by climatic factors as well.

Regardless of the essential reduction of air pollution, defoliation of damaged Scots pine stands still increased for a certain period. Lag of several years in positive changes of tree crown condition in the reduced environmental pollution can be noticed on regional level as well. It is expedient to coordinate the observations of tree crown condition with the investigations of radial tree increment, taking into account a rather big inertia in tree crown condition changes and a low accuracy of visual estimations of crown defoliation.

The rate of recovery of survived heavier damaged trees is higher and convergence of defoliated to a different extend stands and trees is a characteristic feature of the recovery period. No defoliation threshold has been determined beyond which recovery of trees becomes impossible. Crown recovery of more than quarter of damaged trees was registered even in the case of 90% defoliation. Crown recovery rate of larger (dominant) trees is higher than for suppressed ones within the same defoliation level. The impact of stand density on the rate of recovery is negative—the higher density (more intensive competition), the slower recovery of damaged trees.

Dependence of tree increment on crown defoliation is well expressed by a logistic curve. Increment decreases comparatively slightly while defoliation increases until 25–30%, further increase of defoliation leads to essentially higher increment losses, however having achieved 65–70%, increase of defoliation does not result such intensive decrease of tree increment. Impact of crown defoliation on tree increment markedly depends on quantitative parameters of trees. While defoliation of large trees increases from 5 to 75%, their radial increment decreases 3–4 times, whereas the increment of thin trees in the same defoliation interval decreases about 1.5–2 times.

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