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NIEPOŁOMICE FOREST—A GIS ANALYSIS OF ECOSYSTEM RESPONSE TO INDUSTRIAL POLLUTION

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Abstract

The Niepołomice Forest is located near the city of Kraków (Southern Poland). Since the erection of large iron works in the 1950's, the forest has suffered from heavy pollution with SO_2 and industrial dusts containing heavy metals. During the last 10 years this impact was significantly reduced. In the same period the Niepołomice Forest ecology has been intensively studied. With the advent of modern, computer intensive techniques, data gathered in the past are being reanalysed with respect to the spatial and temporal variation of the forest ecosystem response to the industrial pollution. To that end, the effects of natural conditions (soil, vegetation) and of industrial pollution (heavy metals, sulphur dioxide) upon the pine stands (tree volume increment, crown injuries) in the Niepołomice Forest were studied using a geographic information system. Procedures of statistical analysis involving bootstrapping were developed. Results suggest fertilization of forest stands due to industrial pollution, an effect not revealed in former studies. © 1997 Elsevier Science Ltd. All rights reserved

INTRODUCTION

The Niepołomice Forest, an ancient forest complex situated close to the urban and industrial area of Kraków (Southern Poland), may be regarded as an object of a large- scale ecological experiment. In the 1950's, the forest was suddenly exposed to enormous industrial pollution which increased steadily until the end of 1980's, and then decreased (Fig. 1). The pollution was due to the extensive development of metallurgic industry and the subsequent production limitation and technological improvements—a pattern clearly reflecting the political changes in the country. This situation provides a unique opportunity to study the response of forest ecosystems to severe pollution impacts.

The Niepołomice Forest is a forest complex (approximately 110 km^2), including a variety of soils and vegetation types. For many years the forest ecosystems of Niepołomice were the subjects of research for many scientific institutions in Kraków. This activity resulted in hundreds of publications (Banasik, 1978), including two synthesising volumes (Kleczkowski, 1981; Grodziński *et al.*, 1984). However, the vast body of data could not be fully exploited. With the advent of efficient computer-intensive methods such as geographic information systems (GIS), a more advanced analysis of the spatial and temporal variation can be undertaken, and an explanation of the emerging patterns can be attempted.

The aim of this study is to reanalyse the available data on Niepołomice Forest ecosystems using GIS to reveal possible spatial correlations between environmental conditions, pollution levels, and the indices of tree stand quality. The data have not been collected expressly for the purpose of such analysis and therefore a number of methodological problems must be solved.

MATERIALS AND METHODS

As a basis for the GIS database, published topographic and thematic maps of Niepołomice Forest areas were used: (1) 1:25 000 topographic map; (2) 1:20 000 forestry compartment map; (3) 1:37 500 potential vegetation map (Gruszczyk, 1981); (4) 1:37 500 present vegetation community (Ćwikowa and Lesiński, 1981); (5) 1:37 500 forest soils map (Gruszczyk, 1981*a*); (6) 1:37 500 site type map (Gruszczyk, 1981*b*); (7) 1:37 500 overstory stand type map (Mączyński, 1981). The GIS (ARC Info) data base was originally developed at Michigan Technological University. After scanning and editing the maps were registered to UTM co-ordinates using numerous GPS readings made in the field (see Weiner *et al.* 1995 for a detailed description of the GIS development). The database was converted to IDRISI 4.0 format (Eastman, 1992) and the subsequent data input and analysis was performed at the Jagiellonian University in Kraków using the latter system.

The basic information on the Niepołomice Forest is contained in the GIS layers such as soils (Fig. 2) or forest stands (Fig. 3) which are the electronic representations of the maps published before. New maps were produced based on published quantitative

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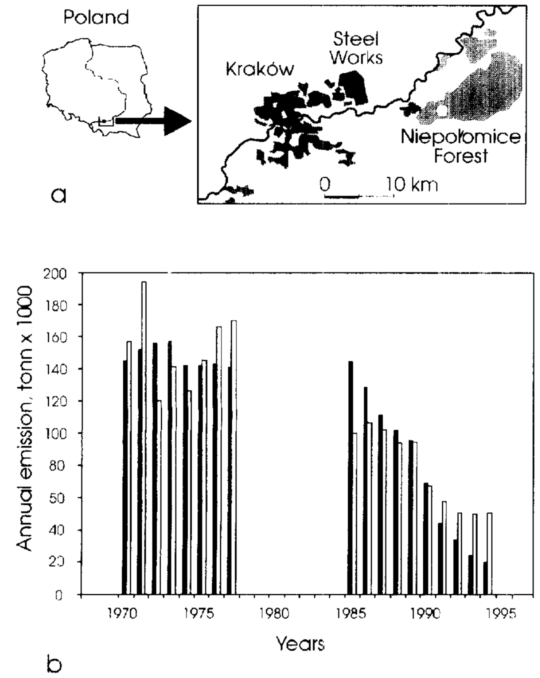


Fig. 1. (a) Location of the Niepołomice Forest in relation to Kraków urban agglomeration and the industrial center. (b) Changes in the total emissions of industrial dusts (filled bars) and sulphur dioxide (open bars) in Kraków agglomeration (after Turzański and Wertz, 1995, and other sources). Note the distinct decrease of pollution during the last 10 years and an increased disproportion of dust and SO_2 emissions in the last five years which may lead to increased acidification).

data. The sources available usually contain precise numerical information about the variable of interest but the spatial co-ordinates for each sampling location are quite general. In most cases only the number of a forest compartment or subcompartment is provided and no better accuracy can be derived after the passage of 20 or more years since the field research was done. The forest subcompartments in Niepołomice can be of various sizes and shapes, sometimes not larger than 100 m^2, but a standard forest compartment is 400×800 m in size. Moreover, sampling for different variables was performed in different locations, although the sampling intensities were quite dense. Thus, a direct use of the data for multivariate analysis is impossible because one cannot order the field data in sets of exactly corresponding spatial variates. An approximate analysis can be made by comparison of maps produced by the spatial interpolation of point data. This can be done only under a premise that the variables studied are continuous (forming a spatial gradient), at least locally. It was assumed that this condition holds in the case of the variables used. The point locations were put into the geometric center of the area identified in the field data files as a number of forest compartment or subcompartment.

The spatial interpolation procedure INTERPOL of IDRISI package (Eastman, 1992) using distance-weighed averages, with weights equal to the reciprocal of the distance squared was used; the search radius was limited to six control points. In this way the interpolated values in the close proximity of a control point (the area most probably encompassing the unknown exact position of a given measurement) could maintain a relatively small variation, which diminishes possible errors.

Most of the data came from the larger, southern part of Niepołomice Forest (mostly pine stands, Fig. 3). The following data on industrial pollution and ecosystem response were used:

1. Index of tree crown injuries (Grabowski, 1981). This index combines various estimates of damage to pine needles and malformations of twigs and branches, most probably caused by SO_2 pollution.

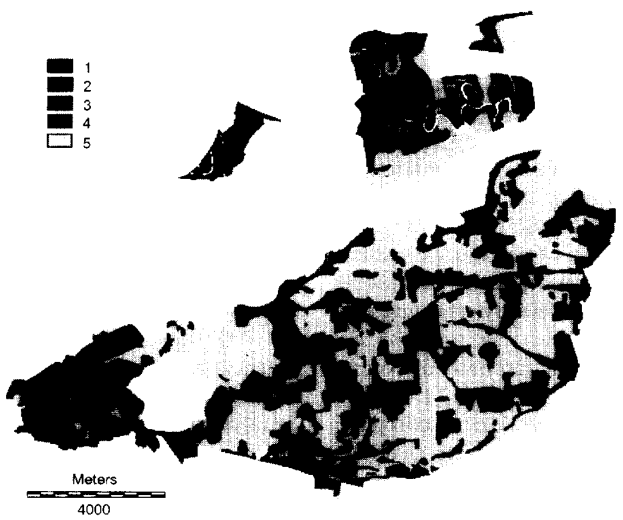


Fig. 2. The soils of Niepołomice Forest (an IDRISI map). (1) Proper brown (mesic) soils; (2) podsolic and cryptopodzolic soils; (3) brown podsolized soils; (4) moist soils, black earths; (5) seasonal gleyish soils (after Gruszczyk, 1981, generalized).

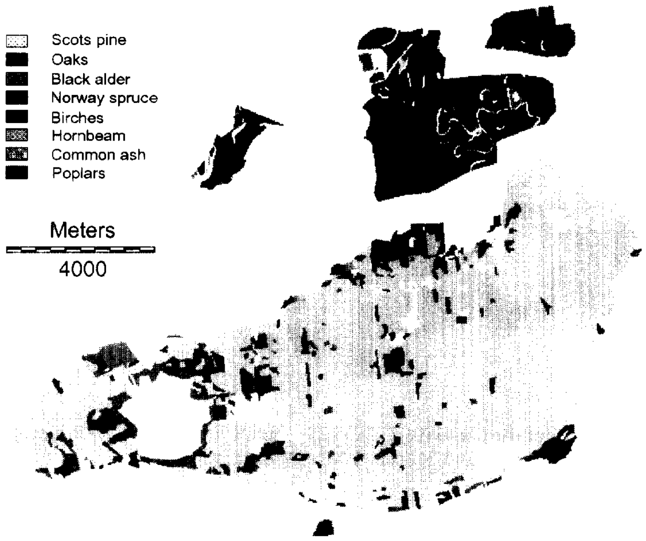


Fig. 3. Forest stands classified by dominant species (IDRISI map, after Mączyński, 1981).

Details of the field data collection and computation procedures are given in Grabowski, 1981. Spatial interpolation of 86 data points resulted in a map (Fig. 4; variable DAM).

2. Index of heavy metal accumulation. The content of six heavy metals (Cd, Pb, Zn, Cu, Fe, Mn) was measured in mosses at 15 locations in 1975 and in 1992 (Godzik and Szarek, 1993). From these point data interpolated maps have been produced. The contents of all metals are strongly intercorrelated, because they occur in relatively constant proportions in the industrial dust from steel works. The first principal component derived by the IDRSI procedure PCA (Eastman, 1992) from six heavy metals (variable PC1) explains over 90% of the total variation and it may constitute a general index of contamination with industrial dusts, which contain many other elements besides heavy metals (Fig. 5).
3. Indices of tree volume increment (Rieger, 1987; Rieger *et al.*, 1987*a*,*b*; J. Raimer, S. Orzeł, unpublished data). A detailed dendrometric survey of pine stands was carried out at 114 locations of the southern forest complex in 1981. The plots were located in younger (A: 20–45 years) and older (B: 60–130 years) stands. The data set, combined from published and unpublished information, includes: tree age, height, diameter at breast hight (d.b.h.), and a numerical index of diameter increment dynamics during the last five years preceding the study, as related to the previous 5-year period (variables WZDA and WZDB for younger and

Fig. 4. Index of tree crown injuries in the southern part of Niepołomice Forest (interpolated from the point data of Grabowski, 1981). Arbitrary units.

Fig. 5. First principal component (PC1) of the contents of six heavy metals in mosses in 1975 (interpolated from the data of Godzik and Szarek, 1993). Arbitrary units.

older age classes, respectively; Fig. 6). Unfortunately, the original data on tree ring diameters were not accessible.

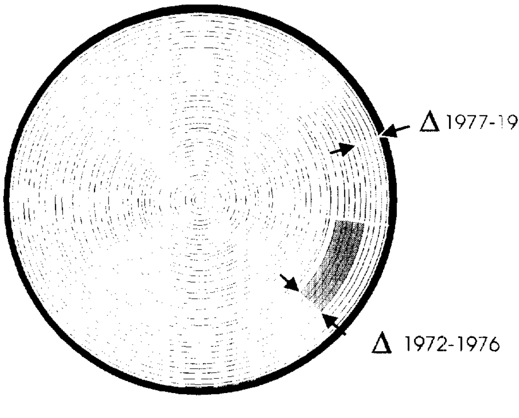
Another index was calculated from the data as a residual of the regression line of tree volume upon age. The tree volume was calculated from height and d.b.h. according to allometric formulas and empirical parameters given for Scots pine by Suliński (1993). The residuals make up an index of cumulative volume increment during the whole life of a tree as related to the average tendency in the whole forest (variables TVRA and TVRB for younger and older age classes, respectively; Fig. 7)

The first index (WZDA, WZDB) should represent the recent changes in tree condition (e.g. related to changing pollution), while the second one (TVRA, TVRB) should depend more on the natural stand quality. The maps of both indices were obtained by a spatial interpolation of point data for younger (A) and older (B) age categories separately (Figs 8 and 9).

DATA ANALYSIS AND DISCUSSION

Characteristic patterns of spatial distribution of environmental and forest response variables is apparent at a first look on the maps. The areas most exposed to industrial dust pollution demonstrated an accelerated tree volume increment (cf. Figs 5 and 8). There was no visible association between the index of heavy metal contamination and the injuries of tree crowns (cf. Figs 4 and 5).

The variables represented on maps by values obtained from spatial interpolation cannot be directly subject to a statistical analysis because they have extremely high autocorrelations (Moran's I in the range of 0.95–0.99 for different variables studied; IDRISI procedure



$$\mathrm{WZD} = \frac{\Delta\,1977\text{-}1981}{\Delta\,1972\text{-}1976} \times 100$$

Fig. 6. Definition of the index of tree ring diameter dynamics WZD (Rieger, 1987; Rieger *et al.*, 1987*a*,*b*;).

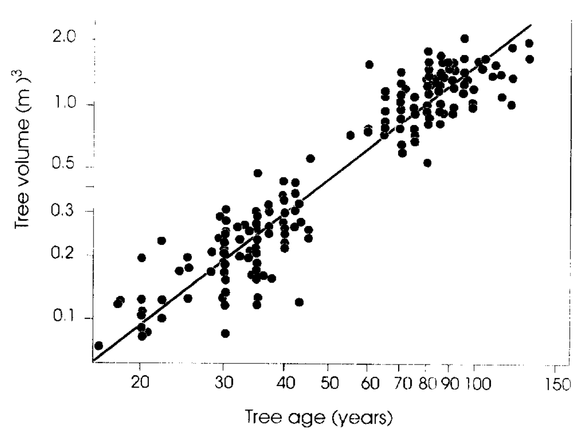


Fig. 7. Regression of pine tree volume upon age in southern part of Niepołomice Forest (double logarithmic plot). Data from Rieger (1987); Rieger *et al.* (1987*a*,*b*) and from J. Orzeł, J.Raimer (unpublished), tree volume estimated after Suliński (1993). Residuals for a given age represent a cumulative tree volume increment index (TVR).

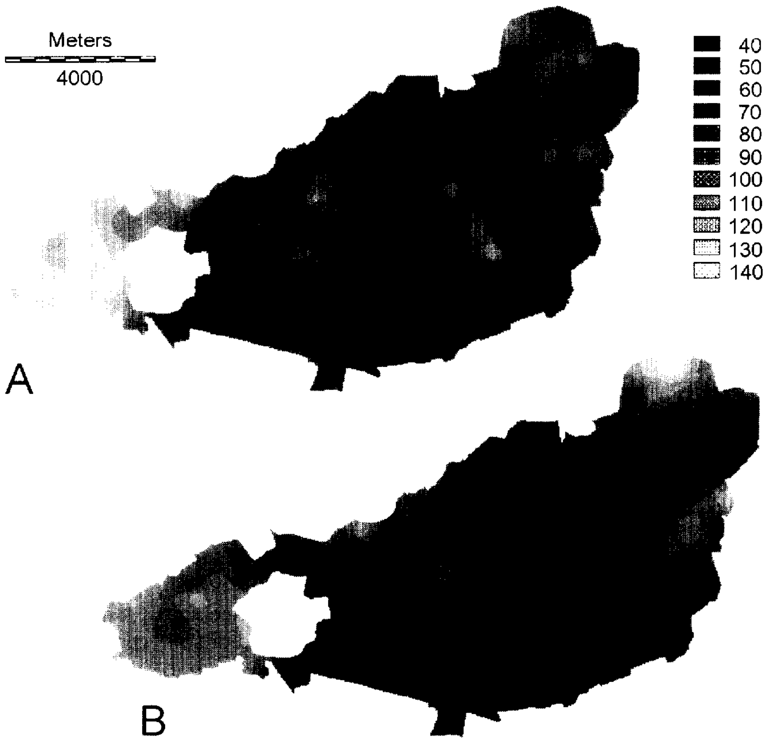


Fig. 8. Index of tree ring diameter dynamics (WZD, per cent) in southern part of Niepołomice Forest. WZD = 100 % means an equal rate of tree ring diameter increment during 5-year periods 1977–1981 and 1972–1976; WZD > 100% denote acceleration of growth, WZD < 100% growth retardation. (A) Pine stands 20–45 years old, (B) pine stands 60–130 years old.

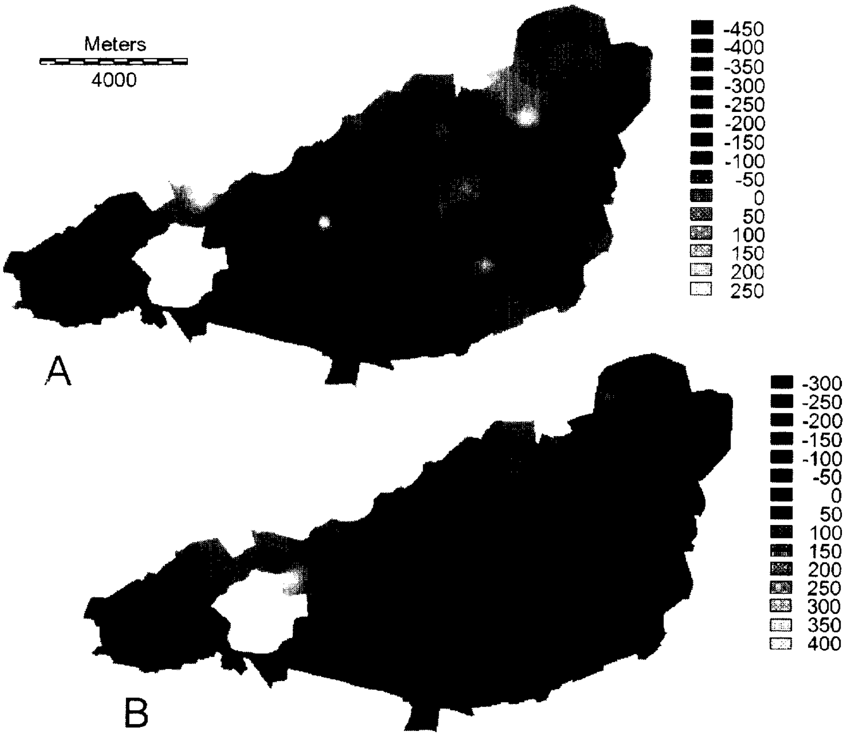


Fig. 9. Cumulative index of tree volume increment (TVR) in southern part of the Niepołomice Forest (arbitrary units). (A) Pine stands 20–45 years old; (B) pine stands 60–130 years old.

AUTOCORR, Eastman, 1992). The occurrence of autocorrelation is inherent in empirical distributions of variables of this kind (Legendre, 1993). An additional autocorrelation component is introduced by the procedure of spatial interpolation. This may cause an overestimation of significance of test statistics (Legendre, 1993). To minimize this effect a randomization ('bootstrap') procedure was used (Noreen, 1989). The variables of interest were sampled from a limited set of randomly selected point locations. Simulations revealed that with a decrease of the number of sampling points (from the original total number of pixels of appr. 870 000) the coefficient of autocorrelation (Moran's *I*) steadily decreases to a value of about 0.7 at approximately 1000 points and then its variation increases (Fig. 10). Accordingly, the sample size was set on approximately 1500 points. The statistical analysis of association between variables or analysis of variance by categories was performed on these samples. The procedure was repeated (with different sets of random point locations) and average statistics were calculated.

The associations between single variables were examined using Spearman rank correlation coefficient, r_s. Table 1 contains average (± standard deviation, range) correlation coefficients for 12 randomly sampled sets of data. A statistically significant positive correlation ($r_s > 0$, $p < 0.05$) was revealed between the tree growth volume increment indexes (WZDA, WZDB) and the first principal component (PC1) of the heavy metal concentrations, i.e. the relative tree volume increments (independent on age class) were increased in the most polluted areas. The residual volume of older trees (TVRB) was also positively correlated with dust fall (Table 1).

The tree crown injury (DAM) was positively correlated with the indices of tree growth dynamics in both age classes (WZDA, WZDB), but negatively with the residual tree volume (TVRA, TVRB; Table 1). Thus, malformations of tree crowns were associated with an increased tree volume increment in the years immediately preceeding the field studies, but the trees with the most damaged crowns were also the smallest in the sample. There are no grounds for interpreting these correlations in terms of causal relationships until the other factor involved are taken into account.

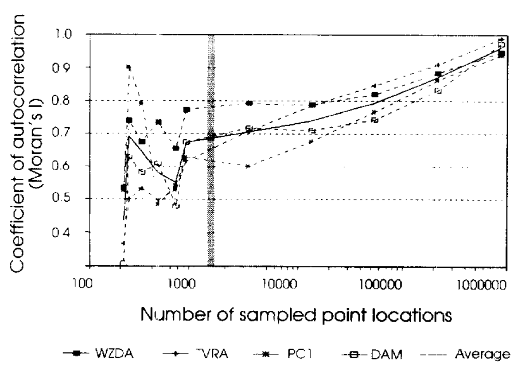


Fig. 10. Changes in the coefficient of autocorrelation (Moran's *I*) with decreasing number of points sampled from spatially interpolated data sets. Grey bar indicates the number of point locations used in analysis.

Five general types of soils have been distinguished in the southern part of the forest (Fig. 2) covering different proportions of the whole area: (1) mesic (brown) soils–5.1%; (2) dry (podsolic and cryptopodzolic) soils–13%; (3) dry/mesic brown podsolized soils–8.1%, (4) wet (black earth, peat-muck) soils—23.7%; (5) seasonally wet (gleyey) soils—50.1%. Soil type exerts a significant effect upon the characteristics of tree stands. The index of acceleration in both age classes (WZDA, WZDB) and the index of tree volume in older class (TVRB) is significantly higher in the most fertile brown (mesic) soils. The total volume (TVRA, TVRB) tends to be the smallest on dry (podzolic) soils ($p < 0.01$; Kruskal–Wallis).

Tree crown damage is highest on brown mesic and in dry podsolic soils. However, in the southern part of the forest the brown (mesic) soils are concentrated at the western edge, in the most polluted area. To discriminate the effects of soil type and dust pollution upon the dendrometric variables, the same statistical analysis was performed within the soil classes. Two distinct patterns persists after the effect of soil type is removed: the positive correlation of the index of dust pollution (PC1) with the indexes of growth acceleration (WZDA, WZDB), and a negative correlation of tree crown injuries (DAM) with tree volume, particularly in older age classes (TVRB), i.e. the greater the damage, the smaller the tree volume. This last phenomenon may indicate for a synergistic effect of poor habitat and gaseous pollution. In the older age class the trees were exposed to pollution during the recent 1/3–1/5 of their lifetime only. Thus, the relatively small volume must have been due to the effect of habitat conditions while the relatively strong malformation of crowns in the weakest individuals is a secondary phenomenon. No correlation was found between the tree crown injuries (DAM) and industrial dust contamination (PC1; Table 1).

A simultaneous effect of two variables (PC1 and DAM) upon the dendrometric characteristics of pine trees was analyzed using the coefficients of determination (R^2) for a multiple regression:

$$Y = a_0 + a_1\mathrm{PC1} + a_2\mathrm{DAM}$$

where PC1 is the dust contamination index, DAM is the pine crown injury index, a_0, a_1 and a_2 are parameters. Table 2 contains the *R2* values and an indication of a positive (+) or a negative (−) effect of the independent variables (the numerical values of regression parameters are omitted). The two independent variables account for 18–29 per cent of variation in dendrometric indices (except for TVRA, i.e. residual volume of trees in younger stands, for which the effect was not significant). These results agree with the Spearman rank correlation patterns for single variables.

Table 1. Average (± standard deviation, range) Spearman rank correlation coefficients for dendrometric variables (WZDA, WZDB, TVRA, TVRB), dust pollution index (PC1) and pine crown injury index (DAM). Correlation coefficient different from 0 ($p < 0.05$) are shaded

	TVRA	TVRB	WZDA	WZDB	DAM
PC1 average	−0.0981	0.3204	0.4917	0.3300	0.0710
Standard deviation	0.0133	0.0195	0.0337	0.0345	0.0208
Minimum	−0.1151	0.2936	0.4439	0.2969	0.0348
Maximum	−0.0734	0.3479	0.5445	0.4271	0.1128
DAM average	−0.1746	−0.2474	0.2429	0.3311	
Standard deviation	0.2573	0.0227	0.0691	0.0666	
Minimum	−0.9870	−0.2782	0.0879	0.1646	
Maximum	−0.0651	−0.2076	0.3111	0.4010	

TVRA is the tree volume index for young stands (20–45 yrs.) TVRB is the tree volume index for older stands (60–130 yrs.) WZDA is the diameter growth index for young stands (20–45 yrs.) WZDB is the diameter growth index for older stands (60–130 yrs.) PC1 is the first principal component of the heavy metal concentrations. DAM is the crown injury.

Table 2. Average (± standard deviation, range) determination coefficients (R^2) for a multiple regression: $Y = a_o + a_l\text{PC1} + a_2\text{DAM}$ where Y-a dendrometric variable (WZDA, WZDB, TVRA or TVRB). The two bottom rows contain the sign of the parameters for respective independent variables: PC1 (dust pollution index) and DAM (tree crown injury index). Values in bold are R^2 values differing from 0 ($p < 0.05$)

	TVRA	TVRB	WZDA	WZDB
R^2 Average	0.0181	**0.1759**	**0.2903**	**0.2081**
Standard deviation	0.0065	0.0203	0.0241	0.0241
Minimum	0.0086	0.1371	0.2571	0.1777
Maximum	0.0281	0.2112	0.3455	0.2501
Sign at a_1 (effect of PC1)	–	+	+	+
Sign at a^2 (effect of DAM)	–	–	+	+

TVRA is the tree volume index for young stands (20–45 yrs.) TVRB is the tree volume index for older stands (60–130 yrs.) WZDA is the diameter growth index for young stands (20–45 yrs.) WXDB is the diameter growth index for older stands (60–130 yrs.) PC1 is the first principal component of the heavy metal concentrations. DAM is the crown injury.

The most probable explanation of this apparent paradox of growth acceleration of trees exposed to highest pollution lays in the high nutritional value of industrial dusts for plants. These pollutants contain, besides heavy metals, a great load of Ca, Mg, N, P and other nutrients (Grodziński *et al.*, 1984), so that the benefit of soil feritilization may outweigh the detrimental effect of heavy metal toxicity, at least temporarily. Moreover, the dust is basic and therefore it can compensate for low pH caused by SO_2 pollution. The recent trend to a decreased dust pollution with a levelled off SO_2 pollutiona (Fig. 1) may change this balance; this makes the above hypothesis testable in the future.

The patterns described above concern the situation in the Niepołomice Forest in late 1970s. In the meantime the level of pollution changed dramatically (Fig. 1). A new field study, repeated 20 years after, could help to confirm or to reject the hypothetical explanation of these effects.

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