Geographic Information System (GIS) Analysis of Ecosystem Response to Industrial Pollution in the Niepolomice Forest in Southern Poland[1]

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Abstract

The Niepolomice Forest is located near the city of Krakow in 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 past 10 years, the ecology of the Niepolomice Forest has been intensively studied and the impact of industrial pollution has been significantly reduced. With the advent of modern computer intensive techniques, data gathered in the past have been reanalyzed with respect to the spatial and temporal variations of the forest ecosystem response to industrial pollution. In addition, the effects of natural conditions (soil, vegetation) and industrial pollution (heavy metals, sulfur dioxide) upon the pine stands (tree volume increment, crown injuries) in the Niepolomice Forest were studied by using a geographic information system. Procedures of statistical analysis involving bootstrapping were developed. Results suggest the apparent fertilization of forest stands as a result of industrial pollution—an effect not revealed in former studies.

Introduction

The Niepolomice Forest, an ancient forest complex situated close to the urban and industrial area of Kraków in 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 amounts of industrial pollution that increased steadily until the end of the 1980's and then decreased (*fig. 1*). This pattern was caused by the extensive development of the metallurgic industry and subsequent production limitation and technological improvements—a pattern clearly reflecting the political changes in the country. These changes provide a unique opportunity to study the response of forest ecosystems to such manipulations.

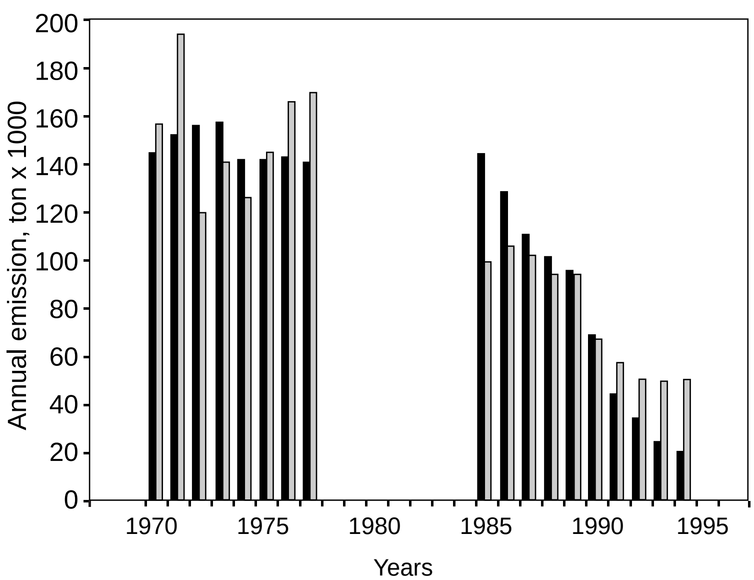

Figure 1 — Changes in the total emissions of industrial dusts (filled bars) and sulfur dioxide (open bars) in the Krakow agglomeration (Turzanski and Wetrz 1995). Note the distinct decrease of pollution during the last 10 years and an increased proportion of dust and SO_2 emissions in the last 5 years which may lead to increased acidification.

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The Niepolomice Forest is a relatively large forest complex (about 110 km^2) which includes a variety of soils and vegetation types. For many years the forest ecosystems of Niepolomice were the subjects of research for many scientific institutions in Kraków. This activity resulted in hundreds of publications (Banasik 1978), including two synthesizing volumes (Grodzinski and others 1984, Kleczkowski 1981). 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. However, the data have not been collected expressly for the purpose of such analysis and therefore a number of methodological problems must be solved.

This paper reports a study that reanalyzes the available data on Niepolomice Forest ecosystems by using GIS to reveal possible spatial correlations between environmental conditions, pollution levels, and indices of tree stand quality.

Methods and Materials

As a basis for the GIS database, published topographic and thematic maps of Niepolomice Forest area were used: 1:25,000 topographic map; 1:20,000 forestry compartment map; 1:37,500 potential vegetation map (Gruszczyk 1981a); 1:37,500 present vegetation community (Cwikowa and Lesinski 1981); 1:37,500 forest soils map (Gruszczyk 1981b); 1:37,500 site type map (Gruszczyk 1981a); and 1:37,500 overstory stand type map (Maczynski 1981). The GIS (ARC Info) methods were developed at Michigan Technological University. After scanning and editing, the maps were registered to Universal Transverse Mercator coordinates using numerous global positioning system (GPS) readings made in the field (Weiner and others 1996). The database was converted to IDRISI 4.0 format (Eastman 1992)[4] and subsequent data input and analysis was performed at the Jagiellonian University in Krakow.

The basic information on the Niepolomice Forest is contained in the GIS layers such as soils (*fig. 2*) or forest stands (*fig. 3*), which are the electronic representations of previously published maps. New maps were produced based on published quantitative data. The sources available usually contain precise numerical information about the variable of interest, but the spatial coordinates 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 Niepolomice can be of various sizes and shapes, sometimes not larger than 100 m^2, but a standard forest compartment is 400 by 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 a 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 by presuming that the variables studied are continuous (forming a spatial gradient), at least locally. It was assumed that this was the condition in the case of the variables used.

Most of the data came from the larger, southern part of the Niepolomice Forest (mostly pine stands; *fig. 3*). Data for industrial pollution and ecosystem response were obtained from the index of tree crown injuries (Grabowski 1981). This index (DAM) combines various estimates of damage to pine needles and malformations of twigs and branches, most probably caused by SO_2 pollution (Grabowski 1981). Spatial interpolation of 86 data points resulted in a map (*fig. 4*).

Data were also obtained from the 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

[4] Unpublished data on file at Department of Forest Mensuration, Agricultural Academy, Krakow, Poland.

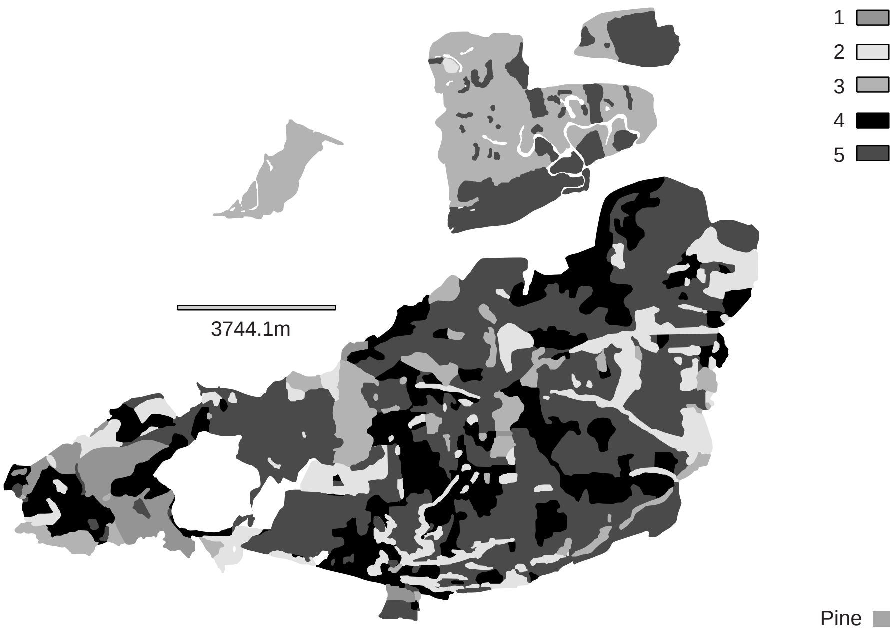

Figure 2 — The soils of the Niepolomice Forest (an IDRISI map): 1--proper brown (mesic) soils (5.1 percent); 2--podsolic and cryptopodzolic soils (13.0 percent); 3--brown podsolized soils (8.1 percent); 4--moist soils, black earths (23.7 percent); and 5--seasonal gleyish soils (50.1 percent) (Gruszczyk 1981).

Figure 3 — Forest stands classified by dominant species (IDRISI map; Maczynski 1981).

interpolated maps have been produced. The contents of all metals are strongly intercorrelated; the first principal component (variable PC1) may constitute an index of contamination with industrial dusts (*fig. 5*).

Indices of tree volume increment were also used (Rieger and others 1987, 1989).[5] 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 height (dbh.), and a numerical index of diameter increment dynamics during the last 5 years preceding the study, as related to the previous 5-year period (variables WZDA and WZDB for younger and older age classes, respectively; *fig. 6*). But, the original data on tree ring measurements were not accessible.

Another index was calculated from the data as a residual of the regression line of tree volume on age (*fig. 7*). The tree volume was calculated from height and dbh. according to allometric formulas and empirical parameters given for Scots pine

[5] Unpublished data on file at Department of Forest Mensuration, Agricultural Academy, Krakow, Poland.

Figure 4 — Index of tree crown injuries in arbitrary units (Grabowski 1981).

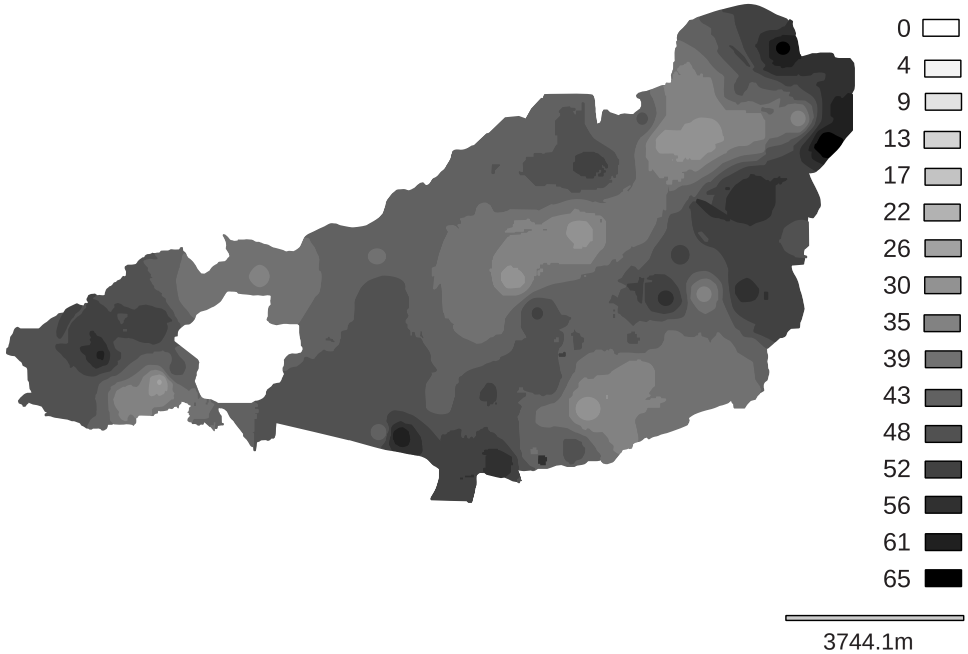

Figure 5 — First principal component (PC1) of the contents of six heavy metals in mosses in 1975 (Godzik and Szarek 1993).

(Sulinski 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).

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

Analysis and Discussion

Characteristic patterns of the spatial distribution of environmental and forest response variables are apparent according to the GIS maps. The areas most exposed

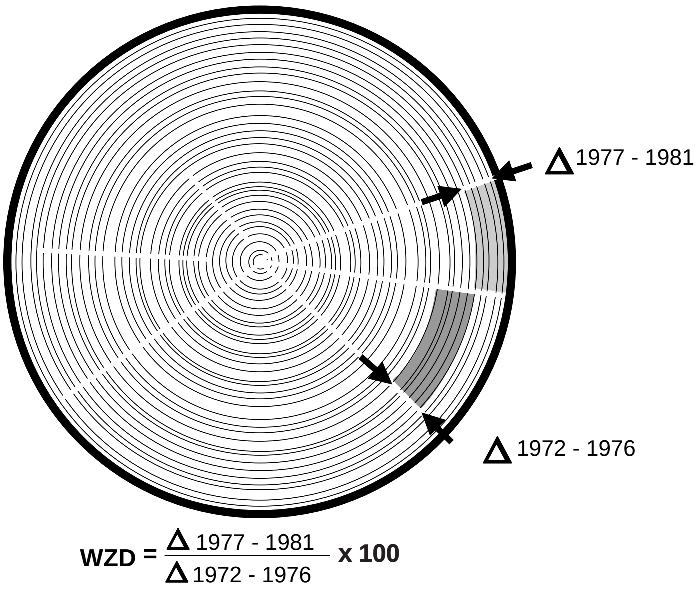

Figure 6 — Index of tree ring diameter dynamics, WZD (Rieger and others 1987, 1989).

Figure 7 — Regression of pine tree volume on age in the southern part of the Niepolomice Forest (double logarithmic plot).[6] Residuals for a given age represent a cumulative tree volume increment index (TVR).

to heavy metal pollution demonstrated an accelerated tree volume increment (*figs. 5, 6*). We did not find visible association between the index of heavy metal contamination and the injuries of tree crowns (*figs. 5, 6*).

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 to 0.99 for different variables studied; Eastman 1992). The occurrence of autocorrelation is inherent in empirical distributions of variables of this kind (Legendre 1993) and 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 about 870,000), the coefficient of autocorrelation (Moran's I) steadily decreases to a value

[6] Rieger and others 1987, Sulinski 1993).

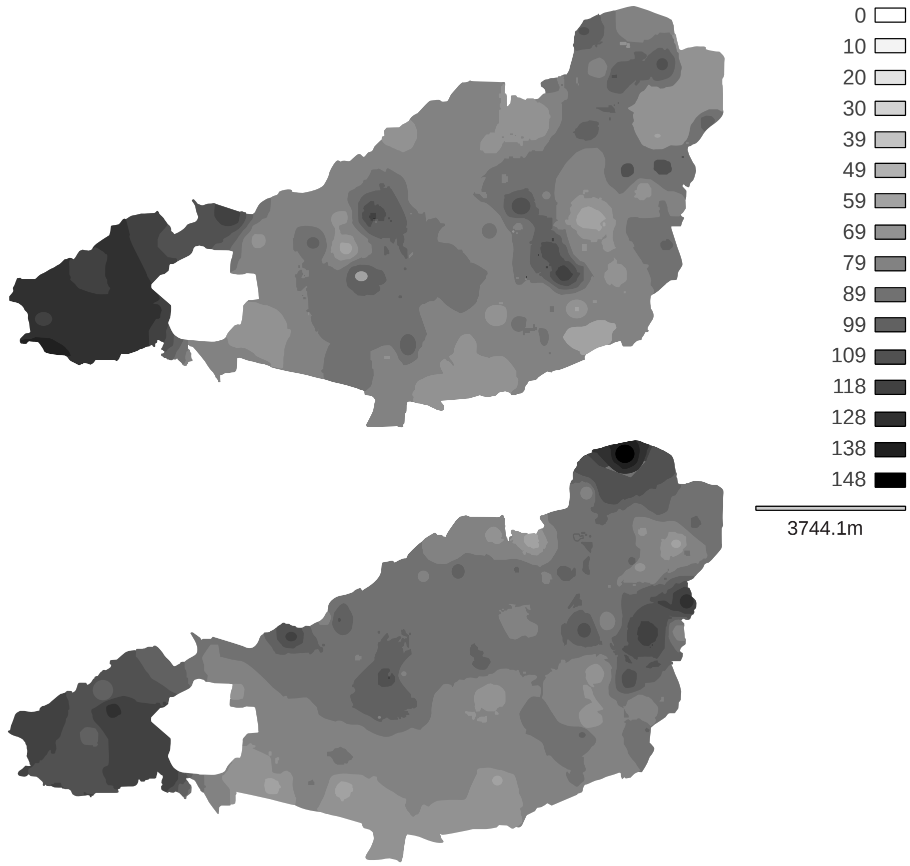

Figure 8 — Cumulative index of tree volume increment (TVR) in the southern part of the Niepolomice Forest (arbitrary units): (*A*) - pine stands 20-45 years old; and (*B*) - pine stands 60-130 years old.

of about 0.7 at 1,000 points and then its variation increases (*fig. 10*). Accordingly, the sample size was set at about 1,500 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 by using Spearman rank correlation coefficient r_s. Correlation coefficients were averaged (± standard deviation, range) for 12 randomly sampled sets of data (*table 1*). A statistically significant positive correlation ($r_s > 0$, $p < 0.05$) was revealed between the tree growth

***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).*[1]

Item	TVRA	TVRB	WZDA	WZDB	DAM
PC1					
Average	-0.098	[2] 0.320	[2] 0.492	[2] 0.330	[2] 0.071
Standard deviation	0.013	0.020	0.034	0.034	0.021
Minimum	0.115	0.294	0.444	0.297	0.035
Maximum	-0.073	0.348	0.544	0.427	0.113
DAM					
Average	[2] - 0.175	[2] - 0.247	[2] 0.243	[2] 0.331	
Standard deviation	0.257	0.023	0.069	0.067	
Minimum	-0.987	-0.278	0.088	0.165	
Maximum	-0.065	-0.208	0.311	0.401	

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

[2] Average correlations that are different from zero (p < 0.05).

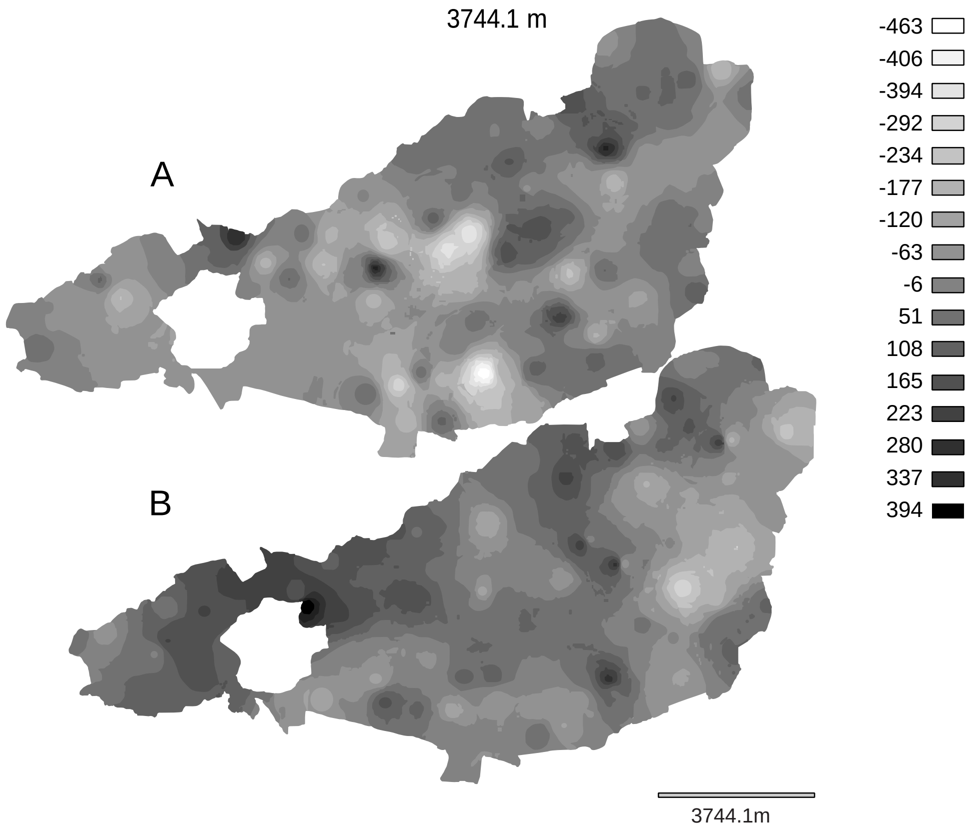

Figure 9 — Index of tree ring diameter dynamics (WZD, percent) in the southern part of Niepolomice Forest: WZD = 100 percent means an equal rate of tree ring diameter increment during 5-year periods 1977-1981 and 1972-1976; WZD > 100 percent denote acceleration of growth, and WZD < 100 percent is growth retardation. (*A*) - pine stands 20-45 years old; (*B*) - pine stands 60-130 years old.

volume increment indices (WZDA, WZDB) and the first principal component (PC1) of the heavy metal concentrations (i.e., the tree volume increments) (independent of age class) were increased in the most polluted areas. The total volume of older trees (TVRB) was also positively correlated with dust fall (*table 1*).

The tree crown injuries (DAM) were positively correlated with the indices of tree growth dynamics in both age classes (WZDA, WZDB), but negatively correlated with the total tree volume (TVRA, TVRB; *table 1*). Thus, a malformation of tree crowns was associated with an increased tree volume increment in the years immediately preceding the field studies, but the trees with most damaged crowns were also the smallest in the sample.

Five general types of soils have been distinguished in the southern part of the forest covering different proportions of the area (*fig. 2*). Soil type exerts a significant effect upon the characteristics of tree stands. The index of increase in both age classes (WZDA, WZDB) and the index of tree volume in older class (TVRB) is significantly higher in 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.

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 persist after the effect of soil type is removed: the positive correlation of the index of dust pollution (PC1) with the indices of growth acceleration (WZDA, WZDB) and a negative correlation of tree crown injuries (DAM) with tree volume, particularly in older age classes (TVRB). In other words, the smaller the tree volume, the greater the damage. This last phenomenon may indicate a synergistic effect of poor habitat and gaseous pollution. In the older age class the trees were exposed to pollution during the recent one-third to one-fifth of their lifetime only. Thus, the relatively small volume must

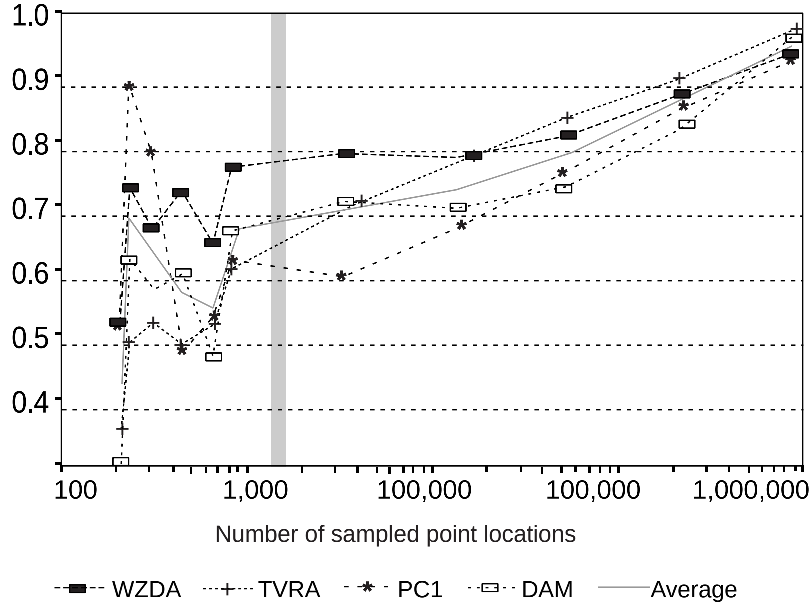

Figure 10 — Changes in the coefficient of autocorrelation (Moran's I) with decreasing number of points sampled from spatially interpolated data sets. Grey bar indicates the number of point locations used in analysis.

have been 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 heavy metal contamination (PC1; *table 1*).

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

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

in which PC1 is the dust contamination index, DAM is the pine crown injury index, and a_0, a_1, a_2 are parameters. The R^2 values were calculated and showed an indication of a positive (+) or a negative (-) effect of the independent variables (the numerical values of parameters are omitted) (*table 2*). The two independent

Table 2 — *Average (± standard deviation, range) coefficients of determination (R^2) for a multiple regression for dendrometric variables (WZDA, WZDB, TVRA, TVRB), dust pollution index (PC1), and pine crown injury index (DAM).*[1]

Item	TVRA	TVRB	WZDA	WZDB
R^2				
Average	0.018	[2] 0.176	[2] 0.290	[2] 0.208
Standard deviation	0.0065	0.0203	0.0241	0.0241
Minimum	0.009	0.137	0.257	0.178
Maximum	0.028	0.211	0.346	0.250
Sign of a_1 (effect of PC1)	-	+	+	+
Sign of a_2 (effect of DAM)	-	-	+	+

[1] TVRA = tree volume index for young stands (20-45 yrs.). TVRB = tree volume index for older stands (60-130 yrs.). WZDA = diameter growth index for young stands (20-45 yrs.). WZDB = diameter growth index for older stands (60-130 yrs.). PC1 = first principal component of the heavy metal concentrations. DAM = tree crown damage index.

[2] Average R^2 values differing from ($p < 0.05$).

variables account for 18 to 29 percent of variation in dendrometric indices (except for TVRA, (i.e., total 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.

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 a great load of Ca, Mg, N, P, and other nutrients (Grodzinski and others 1984) as well as heavy metals. Moreover, the dust is basic and therefore it can compensate for low pH caused by SO^2 pollution.

These patterns describe the situation in the Niepolomice Forest in the late 1970's. Since, then, the level of pollution has changed dramatically (*fig. 1*). A new field of study, GIS, repeated 20 years later, could help to confirm or to reject the hypothesized explanation of these effects.

Acknowledgments

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