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Forest soil acidification assessment using principal component analysis and geostatistics

Luboš Borůvka *, Lenka Mládková, Vít Penížek, Ondřej Drábek, Radim Vašát

Department of Soil Science and Geology, Czech University of Agriculture in Prague, 165 21 Prague 6-Suchdol, Czech Republic

Abstract

Soil acidification and consequent Al release is a problem particularly under forests in mountainous areas of the Czech Republic. It is controlled by a number of factors, like acid deposition, forest type, parent rock, altitude, etc. The Jizera Mountains region presents an area heavily influenced by acidification and forest decline. This paper focused on the effect of stand factors on spatial distribution of soil characteristics of the surface organic (O) and sub-surface (B) horizons from 98 sites using a combination of principal component analysis (PCA) and geostatistics. In the PCA, five principal components (PC) describing more than 70% of total variation were selected. The properties of the O and B horizons (pH, C, N, and S content, potentially dangerous Al forms) were in most cases separated, suggesting different processes and effects in each horizon. Spatial variation of PC scores was analysed using variograms, maps of their distribution were created using kriging. Spatial correlation with stand factors (altitude, slope aspect, forest type and age, soil unit, liming, and grass cover) was analysed using cross-variograms. The surface horizons are more sensitive to external influence (acid deposition, liming, grass expansion) and their spatial variation is stronger. The B horizons are more influenced by forest type (beech vs. spruce) and age, and by soil units (cambic vs. spodic horizons). The effect of stand factors is complex and often indirect. Nevertheless, used combination of pedometrical methods provided concise information about spatial variation and relationships between soil characteristics and the effect of stand factors.

Keywords: Soil acidification; Forest soils; Principal component analysis; Spatial distribution; Geostatistics

1. Introduction

Soil acidification as a natural process is induced by acid parent rocks, high precipitation, and vegetation cover. However, due to human activities this process can be accelerated. Most important anthropogenic factors are forest composition changes, forest management, and particularly deposition of sulphur (S) and nitrogen (N) compounds (Richter, 1986; Kazda and Zvacek, 1989). Loss of base cations, decrease of soil pH, and consequently release of mobile forms of aluminium (Al) and other potentially risk elements are principal consequences of soil acidification (Sposito, 1996). Aluminium release is strongly influenced by organic matter. In natural conditions, most released Al is bound into organic complexes. In contrast, anthropogenic acidification presents a significant input of inorganic acids of S and N that have only a limited ability to form complexes. Anthropogenic acidification is therefore much more dangerous. Moreover, accumulation of acidificants is a long-term process that, unlike the atmosphere, cannot be solved fast by reduction of emissions (Hruška and Krám, 2003). Liming that is used often as soil amelioration measure has some unfavourable consequences as increased carbon (C) mineralization, increased nitrate leaching, or flattening of tree root system (Hüttl and Schneider, 1998; Tyler and Olsson, 2001; Musil and Pavlíček, 2002).

Spatial distribution of soil acidification is controlled by the distribution of stand factors, for example local geology, soil unit (Berggren, 1992; Zysset et al., 1999; Maitat et al., 2000), and vegetation cover (Misson et al., 2001), and, in case of anthropogenic acidification, also by the spatial distribution of acid deposition. Recognizing the factors of the spatial distribution of soil characteristics can enable to distinguish areas with the highest risk of forest damage or subsurface and surface water

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* Corresponding author. Tel.: +420 224 382 751; fax: +420 234 381 836.
E-mail address: Boruvka@af.czu.cz (L. Borůvka).

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pollution. Amelioration measures can be then focused only on these most problematic areas.

In the Czech Republic, soil acidification and consequent Al release is a problem particularly under forest cover in mountainous areas. The Jizera Mountains region presents an area heavily influenced by anthropogenic acidification causing large-scale forest decline. Though the acid emissions decreased significantly in recent years, the ecosystem stays still threatened by acidificants accumulated in soil. In our previous papers, we studied the relationships between soil characteristics by means of basic and multivariate statistics (Mládková et al., 2004, 2005). Spatial distribution of individual soil characteristics in forest floor and in mineral soil horizons and the influence of stand factors were studied in Borůvka et al. (2005a,b). However, a more complex and concise information is needed to show the spatial relationships of soil characteristics and stand factors and to assess the vulnerability of different parts of the area to acidification. Principal component analysis (PCA) as a statistical multivariate method results in data reduction that aims to explain most of the variance in the data while reducing the number of variables to a few uncorrelated components (Sharma, 1996; Anderson, 2003). It enables to identify groups of interrelated variables or individuals. Scores of principal components (PC) represent a specific combination of several characteristics for each statistical unit, i.e. for each location in our study. Spatial distribution of PC scores can thus provide better information about the distribution of soil acidification than the distribution of each individual soil property.

The aim of this study was to identify groups of soil characteristics describing the state of soil acidification using PCA and to analyze spatial relationship of soil acidification with principal stand factors (altitude, aspect, forest type and age, soil unit, liming, grass cover). Spatial distribution of principal component scores should indicate areas with different soil characteristics and different acidification level.

2. Materials and methods

2.1. Area description

The Jizera Mountains region is located in the North of Bohemia (Fig. 1). Altitudes of the sampling sites ranged from 400 to 1000 m. All soils were formed on granite bedrock, so that a strong effect of geology on the spatial variation of soil characteristics cannot be expected. Soils were identified in most cases as Podzols (Haplic or Entic) and Cambisols (mainly Dystric). These soils formed on acid parent rocks under high precipitation causing leaching in the Podzols. Beech (*Fagus sylvatica*), spruce (*Picea abies*), and mixed forests were the prevailing vegetation cover. Forest age was estimated on each sampling site. The highest parts of the mountains were to a large extent covered by grass (*Calamagrostis villosa*) because of spruce forest decline.

2.2. Soil sampling and analyses

The area was covered by an irregular grid of 98 sampling sites. Sampling density corresponded on average to one site per approximately 2 km^2. The grid was designed to cover evenly the whole area and to include different altitudes and aspects, different types of vegetation (spruce, beech, mixed forests), different soil conditions, etc. Samples of the organic (O) horizons (forest floor) and of sub-surface mineral spodic or cambic (B) horizons were collected. Samples were air dried, passed through 2 mm sieves and analysed. pH$_{H2O}$, pH$_{KCl}$, pseudototal contents of Ca and Mg (by atomic absorption spectrometry after aqua regia digestion), and total contents of C, N, and S (by automated analyser LECO CNS-2000; MI USA) were determined (for details see Mládková et al., 2004). Humus quality was assessed by the ratio of soil extract with 0.05 M $Na_4P_2O_7$ at the wavelengths 400 and 600 nm (A_{400}/A_{600}; Pospíšil, 1981).

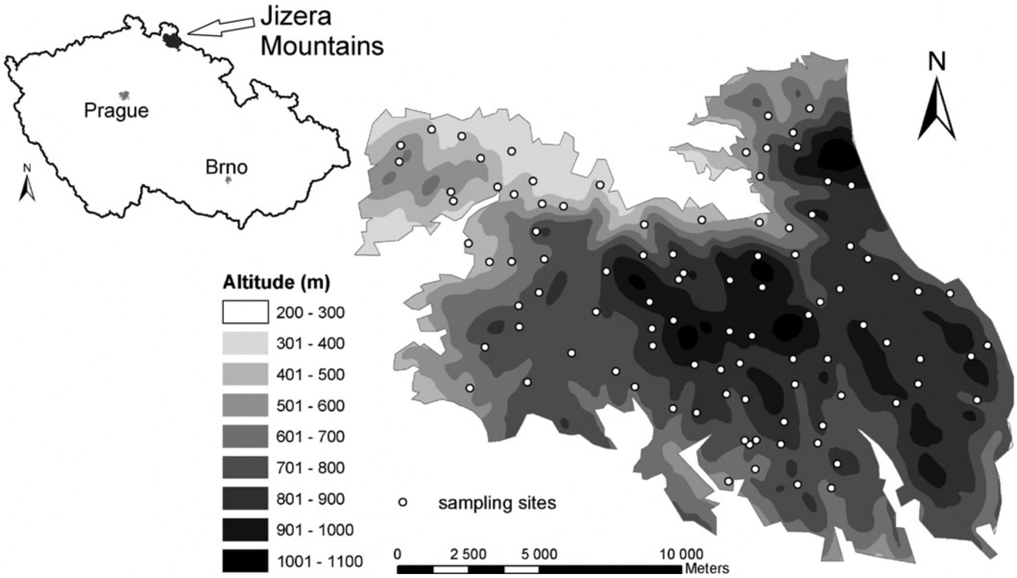

Fig. 1. Location of sampling sites over the relief map. Location of the studied area is shown on the map of the Czech Republic in the top left corner.

Exchangeable Al forms were extracted with 0.5 M KCl solution (Al_{KCl}), an assessment of organically bound Al forms (with a contribution of inorganic forms) was based on Al amounts extracted with 0.05 M $Na_4P_2O_7$ solution ($Al_{Na4P2O7}$; Drábek et al., 2003). Aluminium concentration was determined by means of optical emission spectrometry with inductively coupled plasma (ICP-OES; VARIAN Vista Pro, VARIAN, Australia).

2.3. Statistical treatment

The summary statistics was determined for all soil characteristics. Contents of Ca and Mg in the O horizons and contents of S and N in the B horizons were transformed to their common logarithms due to strong skewness of these data. Correlation analysis was performed. For PCA, all the data were standardized to zero mean and unit variance, and the analysis was done on the correlation matrix. The first five components were retained and rotated using Varimax rotation (Kaiser, 1958); the latter redistributes the variance in each variable so that each contributes strongly to one of the components and little to the others (Sharma, 1996).

2.4. Geostatistical analysis

Geostatistical analysis was performed using the software GS+, Geostatistics for the Environmental Sciences, v. 5.1.1. (Robertson, 2000), and VARIOWIN 2.21 (Pannatier, 1996). All data were standardized to zero mean and unit variance prior to analysis. Variograms were calculated for altitude, cosine of slope aspect, and forest age. Indicator variograms (Deutsch and Journel, 1998) were calculated for forest type (spruce forests were assigned 0, beech forests 1), prevailing soil units (Cambisols were assigned 0, Podzols 1), liming in the past (0 — no liming, 1 — liming; according to data provided by the Forestry and Game Management Research Institute in Jíloviště-Strnady), and grass cover (0 — no grass, 1 — full grass cover). Variograms were calculated also for scores of each principal component.

All the variograms were analysed. Since one aim was to determine spatial correlation between soil characteristics and stand factors, a variogram model fitting most variables was searched. Most variograms could be fitted with a model including nugget and either a spherical structure with the range of 6000 or 9000 m, or both these spherical structures. Therefore, a combined model comprising a nugget and two spherical structures with the ranges of 6000 and 9000 m, respectively, was finally used. Nevertheless, because the spatial dependence of PC scores was in most cases rather weak, only one spherical structure of the fitted model was used for them; the contribution of the other one to the sill (maximum semivariance, C) was considered 0. Weighted least squares method of fitting was used in all cases. The variogram model parameters were determined: the sill, contribution of each spherical structure to the sill, and nugget effect (spatially independent component of the semivariance, C_0). Principal component scores were interpolated by means of block kriging for a regular grid; the distance of block centres was 200 m in both directions. Detailed description of geostatistical theory and computing formulae can be found for example in Deutsch and Journel (1998). Final maps were created using Surfer 7.02 (Golden Software, Inc., Golden, Colorado) and ArcMap 8.1 (ESRI, Inc.) software. Finally, crossvariograms of the spatial relationship between principal components and stand factors were calculated and fitted with the variogram model, where possible. Hulls of perfect correlation (Wackernagel, 1998) were calculated as the limiting values that would hold if correlation (positive or negative) were perfect.

3. Results and discussion

3.1. Basic statistics and correlation analysis

Mean values of soil characteristics, summarized in Table 1, indicate that the soils are strongly acid, with high accumulation of S and N in the forest floor, low humus quality (high A_{400}/A_{600} ratio). Concentrations of potentially dangerous Al forms released due to low pH were rather high, which may lead to toxicity to plants. These results were discussed in detail by Mládková et al. (2004, 2005). Correlation analysis (Table 2) showed some differences between the O and B horizons. In the O horizons, where minimum significant correlation coefficient for $p=0.05$ is 0.197 ($n=98$), pH values are related mainly to the Ca content and to the contents of both Al forms. High Ca content leads to increased pH. With increasing pH, the values of Al_{KCl} decrease and the values of $Al_{Na4P2O7}$ increase. It suggests that at higher pH, Al is bound to less dangerous organic forms. In the B horizons, where minimum significant correlation coefficient for $p=0.05$ is 0.217 ($n=80$), strong inverse relationship between pH values and Al_{KCl} is also apparent. Nevertheless, the correlation with $Al_{Na4P2O7}$ is rather weak. Also the correlation of pH with Ca is weak, while the correlation with Mg becomes more important. In both types of horizons, there is strong positive correlation

Table 1
Statistical parameters of determined soil characteristics (SD= standard deviation)

Characteristic (unit)	Mean	SD	Min.	Max.	Std. error
O horizons					
pH_{H2O}	3.95	0.26	3.5	4.6	0.026
pH_{KCl}	3.20	0.24	2.8	3.8	0.024
C (%)	29.11	6.91	8.1	45.9	0.698
S (%)	0.336	0.105	0.08	0.68	0.011
N (%)	1.494	0.367	0.33	2.42	0.037
Ca (mg kg^{-1})	503.2	361.9	129.0	4450.0	55.14
Mg (mg kg^{-1})	839.5	406.4	214.0	1940.0	41.48
A_{400}/A_{600}	7.43	1.08	4.89	10.39	0.109
Al_{KCl} (mg kg^{-1})	1233.7	507.2	66.8	2890.9	51.23
$Al_{Na4P2O7}$ (mg kg^{-1})	5042.8	2002.1	1969.4	11403.6	202.2
B horizons					
pH_{H2O}	4.00	0.18	2.6	4.3	0.028
pH_{KCl}	3.62	0.22	2.8	4.0	0.032
C (%)	4.23	1.97	0.46	12.35	0.232
S (%)	0.035	0.025	0.01	0.12	0.002
N (%)	0.193	0.087	0.03	0.58	0.011
Ca (mg kg^{-1})	222.5	93.0	69.0	553.0	10.83
Mg (mg kg^{-1})	2564.3	997.6	340.0	5950.0	117.4
A_{400}/A_{600}	9.06	3.00	3.62	19.33	0.335
Al_{KCl} (mg kg^{-1})	805.3	302.7	256.1	1931.5	37.88
$Al_{Na4P2O7}$ (mg kg^{-1})	8589.1	3150.4	2165.8	17885.3	360.9

Table 2
Correlation matrix of soil characteristics in the O and B horizons and correlation between the horizons

	pH$_{\mathrm{H2O}}$	pH$_{\mathrm{KCl}}$	C	S	N	Ca	Mg	A_{400}/A_{600}	Al$_{\mathrm{KCl}}$	Al$_{\mathrm{Na4P2O7}}$
O horizons										
pH$_{\mathrm{H2O}}$	1.000									
pH$_{\mathrm{KCl}}$	**0.715**	1.000								
C	−0.169	−0.138	1.000							
S	−0.169	−0.048	**0.808**	1.000						
N	−0.044	0.008	**0.930**	**0.892**	1.000					
Ca (log)	**0.421**	**0.341**	0.048	−0.154	0.034	1.000				
Mg (log)	**0.269**	**0.261**	**−0.496**	**−0.476**	**−0.494**	**0.390**	1.000			
A_{400}/A_{600}	0.105	0.045	**0.312**	**0.199**	**0.282**	**0.309**	**0.207**	1.000		
Al$_{\mathrm{KCl}}$	**−0.428**	**−0.343**	**0.355**	**0.392**	**0.316**	**−0.496**	**−0.264**	0.165	1.000	
Al$_{\mathrm{Na4P2O7}}$	**0.262**	**0.409**	**0.297**	**0.407**	**0.425**	−0.190	**−0.245**	0.037	**0.210**	1.000
B horizons										
pH$_{\mathrm{H2O}}$	1.000									
pH$_{\mathrm{KCl}}$	**0.819**	1.000								
C	**−0.233**	**−0.460**	1.000							
S (log)	−0.206	**−0.339**	**0.826**	1.000						
N (log)	**−0.293**	**−0.513**	**0.897**	**0.826**	1.000					
Ca	0.191	0.195	−0.065	−0.184	−0.025	1.000				
Mg	**0.382**	**0.478**	−0.207	−0.193	−0.216	**0.420**	1.000			
A_{400}/A_{600}	0.135	0.245	−0.068	0.039	−0.202	−0.146	0.205	1.000		
Al$_{\mathrm{KCl}}$	**−0.626**	**−0.643**	**0.413**	**0.293**	**0.473**	−0.006	−0.128	−0.058	1.000	
Al$_{\mathrm{Na4P2O7}}$	0.061	0.188	0.026	0.004	0.068	0.145	**0.318**	**0.303**	0.007	1.000
O vs. B	**0.263**	**0.305**	0.075	−0.126	0.067	**0.341**	**0.375**	0.052	−0.027	0.037

Correlations significant at $p<0.05$ are in bold.

between C, S, and N contents, indicating binding of S and N as the principal acidificants into organic matter. In the O horizons, these three elements exhibit inverse relationship with Mg content.

Correlation between the O and B horizons is fairly weak, but significant, in case of both types of pH values and Ca and Mg contents. In contrast, correlation of C, N, A_{400}/A_{600}, and Al$_{\mathrm{Na4P2O7}}$ between the horizons is non-significant and very weak, and correlation of S and Al$_{\mathrm{KCl}}$ between the horizons is even negative. The difference in C content is caused by natural organic matter distribution in soil profiles. For S and N it suggests limited mobility of these elements through soil profiles. Differences in Al forms can be caused by different effect of organic matter, different pH values, etc., in the two horizons (Mládková et al., 2005).

Table 3
Correlations between soil characteristics and rotated principal components (PC), and estimated communalities of the variables

Horizon	Characteristic	PC 1	PC 2	PC 3	PC 4	PC 5	Communality
O horizon	pH$_{\mathrm{H2O}}$	−0.006	−0.098	**0.874**	0.153	−0.045	0.798
	pH$_{\mathrm{KCl}}$	0.099	−0.153	**0.809**	0.297	−0.012	0.776
	C	**0.861**	0.044	−0.135	−0.213	0.249	0.868
	S	**0.889**	−0.137	−0.143	−0.151	0.061	0.855
	N	**0.923**	−0.024	−0.017	−0.177	0.198	0.923
	Ca (log)	−0.149	0.069	**0.620**	−0.204	**0.554**	0.760
	Mg (log)	**−0.551**	0.001	0.266	0.263	0.434	0.632
	A_{400}/A_{600}	0.257	0.089	0.096	−0.111	**0.511**	0.356
	Al$_{\mathrm{KCl}}$	0.451	−0.044	**−0.620**	0.122	−0.051	0.607
	Al$_{\mathrm{Na4P2O7}}$	**0.624**	0.054	0.257	0.280	−0.264	0.607
B horizon	pH$_{\mathrm{H2O}}$	−0.188	−0.097	0.179	**0.831**	0.168	0.795
	pH$_{\mathrm{KCl}}$	−0.205	−0.322	0.175	**0.750**	0.348	0.861
	C	−0.013	**0.929**	−0.063	−0.192	−0.020	0.905
	S (log)	−0.081	**0.920**	−0.107	−0.095	0.034	0.874
	N (log)	0.054	**0.930**	−0.009	−0.250	−0.012	0.931
	Ca	0.137	−0.081	0.321	0.060	0.456	0.340
	Mg	−0.024	−0.175	−0.048	0.332	**0.685**	0.614
	A_{400}/A_{600}	−0.480	−0.109	−0.242	0.028	0.416	0.474
	Al$_{\mathrm{KCl}}$	0.062	0.286	0.022	**−0.788**	0.054	0.710
	Al$_{\mathrm{Na4P2O7}}$	−0.049	0.082	−0.086	0.095	**0.557**	0.336
Eigenvalue		3.720	2.897	2.621	2.533	2.250	
% of variation		18.60	14.48	13.11	12.67	11.25	

Correlations with absolute values higher than 0.5 are in bold.

Table 4
Parameters of standardized variograms of principal components (spherical models; C_0-nugget variance, C-sill, C_0/C-proportion of the nugget value from the variogram sill, *a* — range)

Principal component	C_0	C	C_0/C	*a* (m)
PC 1	0.855	1.047	0.816	9000
PC 2	0.500	1.025	0.488	6000
PC 3	0.885	1.031	0.858	6000
PC 4	0.519	1.038	0.500	6000
PC 5	0.794	1.120	0.709	6000

3.2. Principal component analysis

In the PCA applied to the correlation matrix, the first five principal components were selected; they accounted for more than 70% of the total variation. Though the contribution of the fifth PC to the explanation of total variation is rather small, it shows still correlations above 0.5 with at least two soil characteristics, which was used as a criterion. The components were rotated using Varimax rotation; Table 3 gives the rotated loadings, i.e. the correlations between the components and original soil characteristics as variables, and communalities of the variables.

The loadings on the first component (explaining 18.6 % of total variation) are large for C, S, N, and $Al_{Na4P2O7}$ contents in the O horizons. It indicates organic matter accumulation and binding of S and N from deposition in this organic layer. High organic matter content creates conditions for Al binding into organic substances. Large negative loading of the first component is for Mg, highlighting its inverse relationship with the principal acidificants. The loadings on the second component (14.5 % of total variation) are large for C, S, and N content in the B horizons. No apparent relationship of PC 2 with other variables or with the element contents in the O horizons is apparent. The loadings on the third component (13.1% of total variation) are large for both pH types and Ca content in the O horizons and negative for Al_{KCl} in the O horizons. The positive effect of Ca on pH increase and Al_{KCl} content decrease is shown. As the loading of Ca is larger in the O horizons than in the B horizons, it suggests the effect of liming. The fourth component (12.7% of total variation) has large positive loadings for both types of pH in the B horizons and large negative loading for Al_{KCl} in the B horizons. It suggests that exchangeable Al release is controlled primarily by soil reaction in the B horizons. Unlike the O horizons, the relationship with Ca contents is very weak here, while Mg content is more important. The last component (11.3% of total variation) has fairly large loadings for Ca and Mg contents and A_{400}/A_{600} in both horizons, and $Al_{Na4P2O7}$ content in the B horizons. It indicates the effect of geogenic base elements, in contrast with added Ca manifested in PC 3, and the effect of humus quality. In the B horizons it shows that at presence of lower quality humus (higher A_{400}/A_{600}) and higher Mg and Ca content, more Al is bound in organic substances.

The communality describes the proportion of the variability of each characteristic that is explained by the PCA model. It shows that the variability of most characteristics is described pretty well. Exceptions with low communality values are A_{400}/A_{600} ratio in both horizons, and Ca and $Al_{Na4P2O7}$ in the B horizons. These characteristics exhibit generally weaker relationships with other characteristics.

3.3. Geostatistical analysis

Spatial dependence of principal components is rather weak, with high proportion of nugget effect in the variograms (Table 4, Fig. 2). The highest proportion of nugget variance was found for PC 1 and 3. PC 1 is related to acid deposition that can vary strongly according to relief parameters, wind direction, etc. PC 3

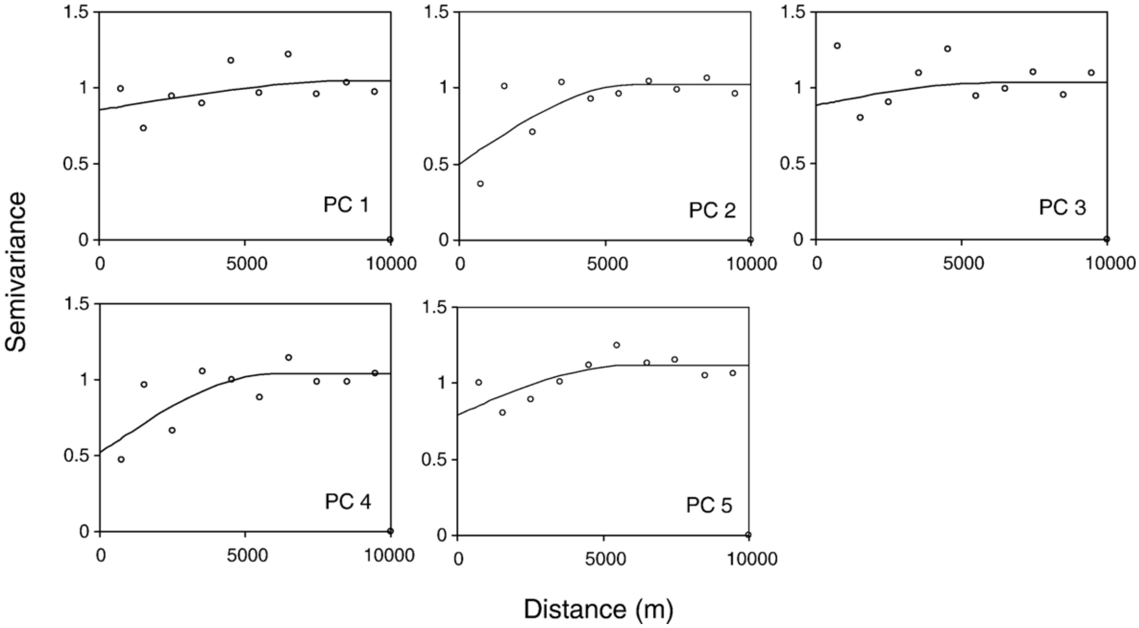

Fig. 2. Variogram of principal component scores (standardized values).

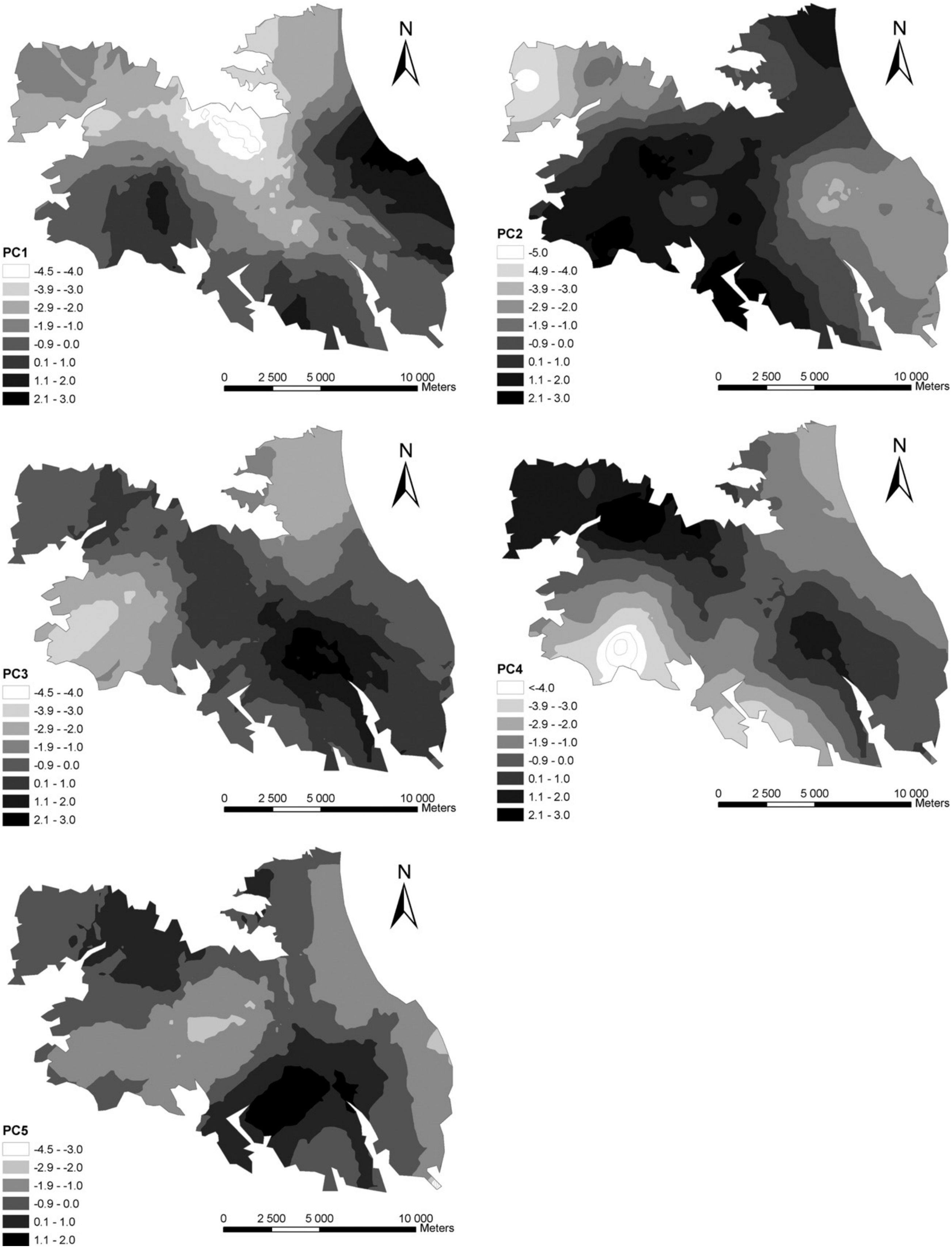

Fig. 3. Kriged maps of principal component scores.

is related most probably to liming. Both effects result primarily from anthropogenic activities and not from natural development. Stronger short-scale variability can therefore be expected. The other three PC showed large loadings for some characteristics of the B horizons. Though these may be also affected by human activities, there is a stronger influence of natural processes and conditions modifying the output, so that the spatial dependence is stronger.

Kriged maps of the spatial distribution of principal components are shown in Fig. 3. Dark areas on the map of PC 1 represent localities with high C, S, N, and $Al_{Na4P2O7}$ content and low Mg content in the forest floor. It should represent the areas with the strongest acidification. However, the areas with high scores of the PC 1 are limited to the south-western part, where the highest acid deposition can be expected because of prevailing western winds in this area, and on the eastern edge. The central part that was strongly damaged by acidification shows lower scores. This can be attributed to liming of the upper parts of the mountains done in the 1980’s and 1990’s. Effect of liming is probably manifested on the map of PC 3, where the high score values represent areas with high Ca content, higher pH and lower Al_{KCl} in the O horizons. However, the effect of liming is generally limited to the surface layer. Though the reliability of the map for PC 3 is limited because of high variogram nugget proportion and wide spread of the semivariance values, it still can serve as an illustration of the spatial distribution of the values and spatial trends. In the B horizons of the central part of t he region, contents of C, S, and N are still rather high, exhibited as high scores of PC 2. The distribution of PC 4 scores shows maxima at the north-western part of the area; positive values are also on a small area on south–east. These areas have higher pH and lower Al_{KCl} content in the B –horizons. These two areas correspond to two areas of beech forests, while the forests of the rest of the region are dominated by spruce. This could confirm positive effect of broadleaved species compared to coniferous trees, especially spruce (for example Rothe et al., 2002; Brandtberg and Simonsson, 2003). The fifth PC scores show maxima at the southern part of the region, positive values are also at the north-western part. These areas have high Mg and Ca content and can be attributed to slight differences in parent material composition with respect to Mg content. Nevertheless, an effect of beech forests causing weaker Mg soil depletion compared to spruce forests is also possible on this PC, especially in the north–west. In the central part of the region, where the scores of PC 5 are negative, a positive effect of grass expansion on soil chemistry could have taken an effect (Fiala et al., 2001). Though it is an area depleted of Ca and Mg, grass expansion produces organic matter of better quality which can bind Al into less dangerous organic complexes, at least in the surface soil layers.

3.4. Spatial relationship with stand factors

The effect of stand factors mentioned in the previous section based on spatial distribution of principal component scores was further analysed by means of cross-variograms and their comparison with the hulls of perfect correlation (Fig. 4). Most cross-variograms are far from perfect correlation. It implicates that no component, and consequently no soil characteristic or process, is controlled entirely by a single factor. In contrary, each component is controlled by several factors that can support or contradict each other. Nevertheless, effects of some factors are more pronounced than the other ones for each PC.

The first PC showed spatial relationship with altitude, forest type, and soil unit. As this component comprises mainly the content of C, S, N, and $Al_{Na4P2O7}$ in the organic horizons, the positive spatial relationship with altitude means that at higher altitude, the content of these elements increases. Slower decomposition of organic matter due to temperature gradient can take an effect. Stronger acid deposition of S and N in higher altitudes is another explanation. The relationship between PC 1 and altitude and negative loading on PC 1 for Mg can be interpreted as stronger leaching of Mg at higher altitudes due to larger precipitation amounts and larger acidificants input from deposition. Inverse spatial relationship between PC 1 and forest type means that higher PC 1 scores are for sites covered by spruce forests compared to beech forests. It can be again interpreted in two ways: as larger accumulation of organic matter under the spruce, or as higher acidificants interception by spruce trees than beech trees. Both explanation are probable and can be responsible for a part of the result. Weak positive spatial relationship between PC 1 and soil unit means larger organic matter accumulation in Podzols compared to Cambisols, which corresponds to the nature of these soils and their forming. Nevertheless, high loading on PC 1 for $Al_{Na4P2O7}$ indicates that in conditions of high organic matter and acidificants accumulation, more Al is bound in organic, i.e. less dangerous forms.

Spatial relationship between PC 2, comprising C, S, and N content in the B horizons, and altitude can be again related to higher acidificants deposition and organic matter accumulation at higher altitude. The relationship with cosine of aspect specifies that sites with southern (or more precisely southwestern orientation) are more exposed to acid deposition compared to northern orientation. It corresponds to prevailing wind direction in the area. The fact that this component is related mainly to the sub-surface horizons suggests also the effect of increased precipitation at higher altitudes conditioning transport of the acidificants through soil profiles. The relationship between PC 2 and forest age can indicate larger acidificants interception by older trees and consequent stronger transport through soil profiles compared to young forests.

As the third PC most probably demonstrates the effect of liming, it shows clear spatial relationship with this amelioration measure. The relationship with altitude corresponds to the fact that liming was focused mainly to the most elevated areas where the effects of acid deposition were most devastating. Inverse spatial relationship between PC 3 and forest age can be also caused by the localization of liming, or it can indicate increased Ca depletion by old forests. The latter explanation corresponds to findings by Yanai et al. (2005).

The fourth PC is related mainly to forest type: soils under beech have higher pH and lower Al_{KCl} in the B horizons compared to soils under spruce. The relationship between PC 4 and altitude, though very weak, is caused by the fact that the

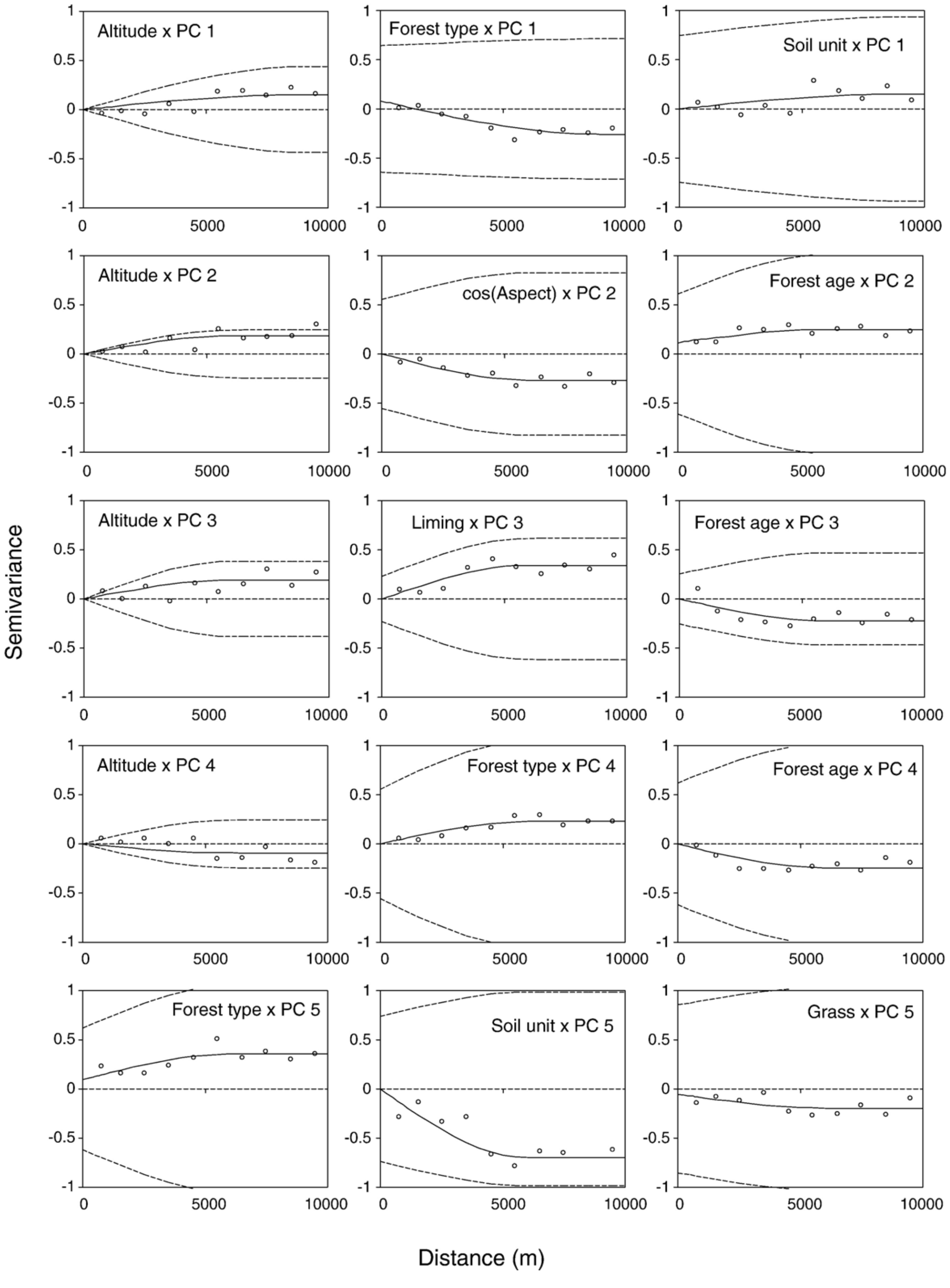

Fig. 4. Standardized crossvariograms of the relationship between stand factors and principal component scores; dashed lines indicate hulls of perfect correlation.

proportion of beech forests diminishes with increasing altitude. Inverse spatial relationship between PC 4 and forest age indicates that older stands have lower pH in the B horizons and higher amounts of potentially dangerous Al forms can be released. Acidifying effects on soil profile of long-time spruce growing is thus manifested.

The scores of PC 5 are related to soil unit, forest type, and grass cover. Inverse relationship with soil unit means lower Ca and Mg content in Podzols compared to Cambisols. It corresponds to the nature of these soils and it can also indicate some slight differences in parent material. This relationship also indicates higher amount of Al_{Na4PO7} in the B horizons of Podzols, which highlights the difference between spodic horizons of Podzols rich in organic matter and cambic horizons of Cambisols. Moreover, this Al fraction can be contributed, in addition to organic Al forms, also by Al bound on Fe oxides. These oxides are again generally more abundant in spodic horizons than in the cambic ones. The positive relationship between PC 5 and forest type means higher Ca and Mg content, or smaller depletion, under beech compared to spruce. The relationship between PC 5 and grass cover suggests the positive effect of grass expansion on surface soil chemistry as mentioned above.

4. Conclusions

Principal component analysis summarized the relationships between soil characteristics influenced by acidification. Application of geostatistics enabled to assess the spatial distribution of the principal components and to analyze the influence of principal stand factors. It was shown that surface horizons are more sensitive to external influence (acid deposition, liming, grass expansion) and their spatial variation is stronger. In the mineral horizons, the effect of pedogenetic processes becomes more important, and the effect of external factors is mediated by soil processes. Generally, the effect of stand factors is very complex. It is therefore difficult to clearly distinguish the effects of the particular factors. Nevertheless, used combination of pedometrical methods provided concise and summary information about spatial variation and interrelations between soil characteristics and about the effect of stand factors. Resulting maps can be used to delineate the areas with different impact of acidification and human activities for further forest management.

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