Factors of spatial distribution of forest floor properties in the Jizerské Mountains

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ABSTRACT

The aim of this contribution was to describe spatial distribution of soil characteristics of forest floor in the Jizerské Mountains region and to assess the effect of stand factors by means of geostatistics, using structural correlation coefficients. Most soil properties showed a low spatial dependence with variogram range of 6000 m. Kriged maps of spatial distribution of soil properties were created. Most characteristics were influenced by altitude. A general decrease of pH and Ca and Mg content and an increase of potentially toxic Al forms (Al_{KCl}) due to high S and N loading were demonstrated. An effect of liming on the decrease of Al_{KCl} content, and higher pH and Mg content and lower Al_{KCl} under beech forest were shown. Lower acidity and a better humus quality were found at higher altitudes under grass cover (*Calamagrostis villosa*) in spite of high S and N content. The ratios S/Ca and S/(Ca + Mg) can serve as an indicator of soil acidification level.

Keywords: soil acidification; spatial distribution; stand factors; forest floor; geostatistics

Soil acidification in the Czech Republic presents a serious problem in forest soils of mountainous areas. Acidification leads to depletion of base cations, pH decrease, development of humus of lower quality, and release of labile Al forms. Stand conditions of each site control the spatial distribution of soil properties. These conditions include the type of parent rock, level and distribution of acid deposition, soil leaching by precipitation waters, forest species composition, forest management, etc. As a result of the effect of stand factors and conditions, the acidification indices may vary strongly from place to place. Lime application, aiming in reducing the acidification consequences, can further increase the variability. Strong variation was observed even at short scales. Chang and Matzner (2000) studied soil variation with the distance from tree stem caused by element fluxes with throughfall and stemflow. Spangenberg and Kolling (2004) showed that acidification due to acid deposition can be different on forest edges compared to the interior parts of closed forest stands, whereas Karltun (1994) studied geographic variation of acidification on a regional level.

Forest floor, i.e. the surface organic horizons of the forest soils, is the upper layer of the soil. It is an important component of biogeochemical element cycling in the forest ecosystem. Ukonmaanaho and Starr (2002) showed its importance in nutrient retention. Unfortunately, this layer is also most exposed to acid deposition and other anthropogenic effects, which makes it very sensitive to changes (Green et al. 1993, Suchara and Sucharová 2002). The effects of liming are usually limited to organic horizons as well; mineral horizons are influenced only slightly (Hahn and Marschner 1998, Musil and Pavlíček 2002). The forest floor can thus well reflect the effect of different external factors.

The Jizerské Mountains region is one of the areas that have been most affected by human activities in last few decades (Suchara and Sucharová 2002). High concentrations of acidificants in atmosphere led to forest and soil damages. Breakdown of forest structure was followed by grass expansion. At present, concentrations of acidificants in atmosphere have decreased. However, forests are still endangered by long-term changes of soil conditions (lower base saturation, lower pH and high labile Al forms concentrations). Distribution of basic soil characteristics in this region was shown by Mládková et al. (2004). The effect of forest types and other stand factors on Al forms is described in Mládková et al. (2005).

The aim of this paper is to describe the spatial distribution of soil properties of the forest floor in the Jizerské Mountains region. The effect of stand

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factors controlling the spatial distribution of soil properties is analysed. Geostatistical methods are used for this purpose.

MATERIAL AND METHODS

The Jizerské Mountains region is located in the north of Bohemia (Figure 1). 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. Altitudes of these sites ranged from 400 to 1000 m. Beech (*Fagus sylvatica*), spruce (*Picea abies*) and mixed forests were the prevailing vegetation cover. The highest parts of the mountains were covered by grass (*Calamagrostis villosa*) to a large extent because of the damage of spruce forest. Soils were identified in most cases as Podzols (Haplic or Entic) and Cambisols (mainly Dystric), all on granite bedrock.

The total depth of the O horizons was recorded, including undecomposed litter layer. Composite samples of the O horizon were collected from the horizons (L + F). Samples were air dried, passed through 2 mm sieves and analysed. The following soil characteristics were determined (for details see Mládková et al. 2004): pH_{H_2O} and pH_{KCl}, humus quality by the ratio of absorbances of sodium pyrophosphate soil extract at the wavelengths of 400 and 600 nm (A_{400}/A_{600}, Pospíšil 1981), total contents of Ca, Mg, C, N and S (Ca_{tot}, Mg_{tot}, C_{tot}, N_{tot}, S_{tot}). Exchangeable Al forms were extracted with 0.5M KCl solution (Al_{KCl}), an assessment of "weakly organically bound" and "total organically bound" Al forms was based on Al amounts extracted with 0.3M $CuCl_2$ (Al_{CuCl_2}) and 0.05M $Na_4P_2O_7$ ($Al_{Na_4P_2O_7}$) solutions, respectively (Drábek et al. 2003). Ratio C/N (w/w) was calculated as another indicator of soil humus quality. Moreover, molar ratios between total S and total Ca (S/Ca) and between S and the sum of total Ca and Mg [S/(Ca + Mg)] were also calculated. These ratios should indicate the balance between acidifying substances represented by S and base soil components.

Geostatistical analysis was performed using the software GS+, Geostatistics for the Environmental Sciences, v. 5.1.1. (Robertson 2000). Variogram was calculated for each soil characteristic. The datasets were transformed for the calculation to the range 0 to 1 for easier comparison of variogram parameters. Spherical variogram models with the ranges of 3000, 6000 or 9000 m were fitted in all cases where a spatial dependence was found. Soil properties were interpolated by means of block kriging; the distance of blocks was 200 m in both directions. Final maps were created using Surfer 7.02 (Golden Software, Inc., Golden, Colorado) and ArcMap 8.1 (ESRI, Inc.) software.

In addition, spatial distribution of stand factors was evaluated. Variograms were calculated for altitudes and cosine of the aspect (Northern exposition was thus assigned 1, Southern exposition –1; East and West were given the value of 0). Indicator variograms (Deutsch and Journel 1998) were calculated for forest type (Norway spruce forests were assigned 0, beech forests 1), soil units

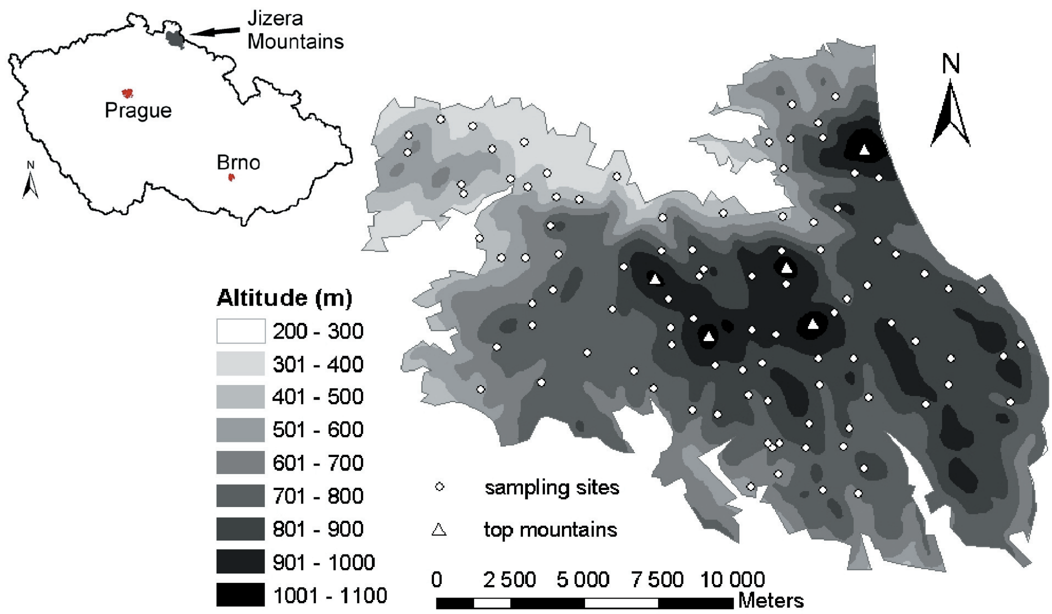

Figure 1. Location of sampling sites over the relief map; location of the studied area on the map of the Czech Republic is shown in the top left corner

(Cambisols were assigned 0, Entic Podzols 0.5, and Haplic 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). These variograms were modelled in a similar way as the variograms of soil characteristics. Finally, crossvariograms of the spatial relationship between soil properties and stand factors were calculated and fitted with spherical models. Structural correlation coefficients, ρ_{uv}, were calculated according to Goovaerts (1992):

$$\rho_{uv} = \frac{b_{uv}}{\sqrt{b_{uu} b_{vv}}}$$

where: b_{uu}, b_{vv} and b_{uv} are the coefficients of structural (spatially dependent) component of the two particular variograms and crossvariogram, respectively. This coefficient could be calculated only under condition that $(b_{uu} b_{vv}) \geq b_{uv}^2$, which is called Schwarz's inequality (Webster and Oliver 2001).

RESULTS AND DISCUSSION

Spatial distribution of soil characteristics

Mean values and standard deviations of the determined characteristics of the O horizon are given in Table 1. It is apparent that in most cases the soils are strongly acid, with low organic matter quality and rather high content of potentially toxic Al forms (Al_{KCl}), as well as organically bound Al forms (Al_{CuCl_2} and $Al_{Na_4P_2O_7}$). A detailed description and statistical analysis of the datasets were published by Mládková et al. (2004, 2005). Here we will focus on the spatial distribution of the variables. Parameters of their variograms (Table 1) show that in most cases the spatial dependence is low, having the proportion of structural variogram component from the sill $(C–C_0)/C$ lower than 0.25 (Cambardella et al. 1994). It indicates a high proportion of nugget variance, which may be caused by a high variation at short distances. Medium spatial dependence was found in case of horizon depth, Mg_{tot}, S_{tot}, N_{tot}, and the ratios S/Ca and S/(Ca + Mg). In contrast, no spatial dependence was found for C/N ratio. Variogram ranges were 6000 m for most characteristics. Al_{KCl} and $Al_{Na_4P_2O_7}$ showed the range of 3000 m, which may be caused by the effect of several factors with different spatial distribution; the factors will be discussed further on. The ratio S/Ca showed longer variogram range of 9000 m.

Figure 2 shows kriged maps of spatial distribution of selected soil characteristics. The extreme values are a little flattened by kriging, especially when the nugget variance proportion is high. The

Table 1. Mean values and standard deviation (*SD*) of the characteristics of the O horizons and parameters of spherical variogram models (C_0 – nugget variance, C – sill, $(C–C_0)/C$ – proportion of the structural variogram component, a – range)

Characteristic (units)	Mean	*SD*	C_0	C	$(C–C_0)/C$	a (m)
Depth (cm)	11.32	3.97	0.025	0.043	0.419	6000
pH_{H_2O}	3.95	0.26	0.050	0.057	0.123	6000
pH_{KCl}	3.20	0.24	0.052	0.059	0.119	6000
A_{400}/A_{600}	7.43	1.08	0.032	0.042	0.238	6000
Mg_{tot} (mg/kg)	839.5	406.4	0.034	0.052	0.346	6000
Ca_{tot} (mg/kg)	503.2	361.9	0.032	0.040	0.200	6000
C_{tot} (%)	29.11	6.91	0.029	0.036	0.194	6000
S_{tot} (%)	0.336	0.105	0.027	0.037	0.270	6000
N_{tot} (%)	1.494	0.367	0.024	0.033	0.273	6000
C/N (g/g)	19.64	1.77	0.037*	0.037	0	–
Al_{KCl} (mg/kg)	1233.7	507.2	0.027	0.034	0.206	3000
Al_{CuCl_2} (mg/kg)	4270.0	1672.8	0.054	0.056	0.036	6000
$Al_{Na_4P_2O_7}$ (mg/kg)	5042.8	2002.1	0.035	0.046	0.239	3000
S/Ca (mol/mol)	12.25	8.71	0.020	0.033	0.394	9000
S/(Ca + Mg) (mol/mol)	2.83	1.85	0.029	0.047	0.383	6000

*pure nugget model

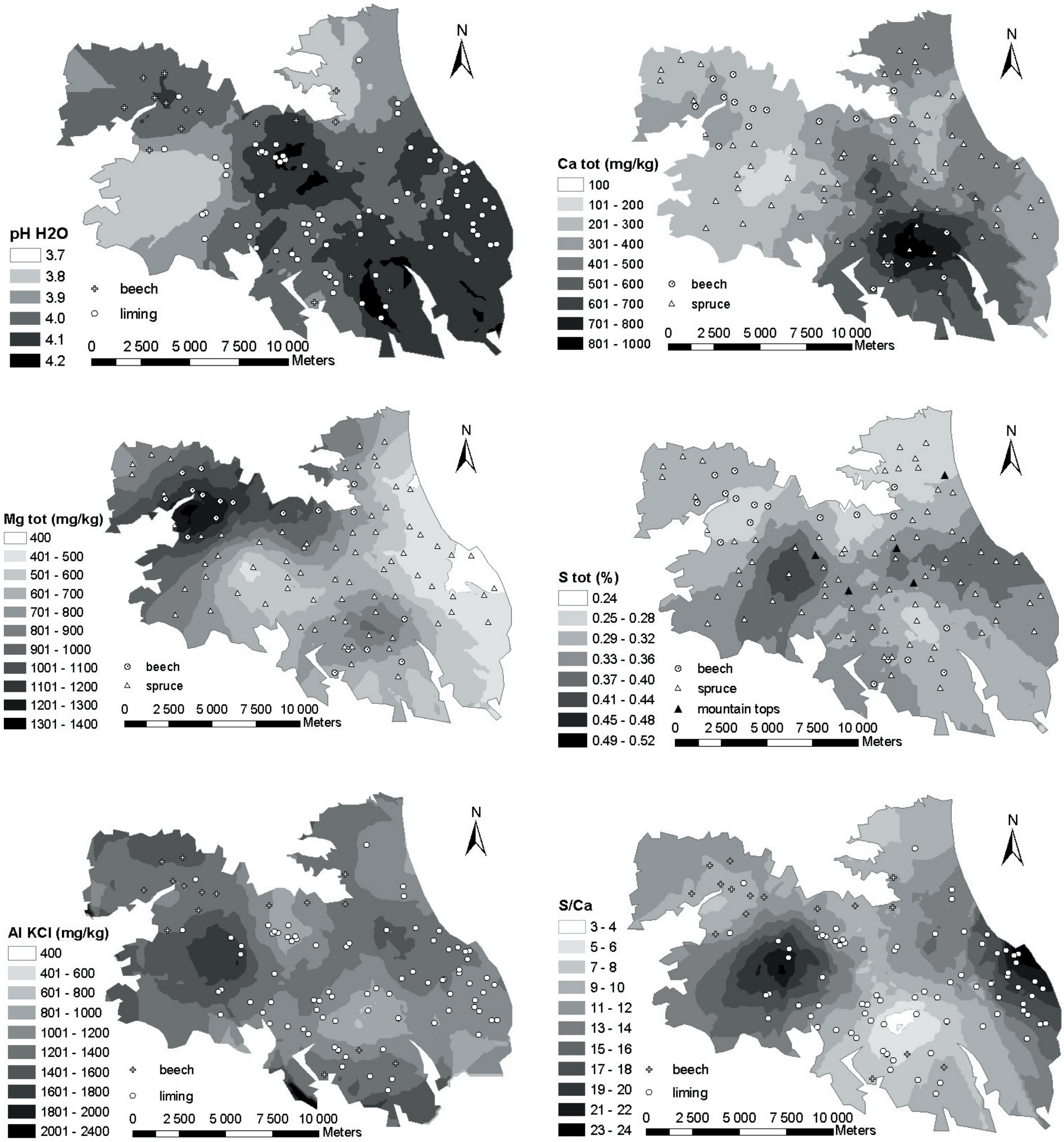

Figure 2. Kriged maps of soil properties of the forest floor; distribution of selected sampling sites with specific stand conditions is shown on each map

ranges of values are therefore smaller compared to the original datasets. Nevertheless, the maps indicate well the spatial trends in the distribution. The highest values of pH_{H_2O} are in the central and south-eastern part of the area. This distribution corresponds to some extent to the area limed in the past. Another area with higher pH values is situated in the northwest of the area. Areas with the lowest pH values cover southwest and northeast of the region. Similar distribution was found for pH_{KCl} (map not shown). The largest Ca_{tot} corresponds to a large extent to the limed area. In contrast, Mg_{tot} is little affected by liming, though dolomitic limestone was used. Magnesium leaching to deeper horizons due to its higher mobility compared to Ca or its plant uptake may have taken the effect. The largest Mg_{tot} content is located under the beech forest in the northwestern part of the region. The smallest Mg_{tot} values are in the eastern part of the region and in the centre of the western half of the

Table 2. Parameters of variograms of stand factors (spherical models; C_0 – nugget variance, C – sill, $(C–C_0)/C$ – proportion of the structural variogram component, a – range)

Stand factor	C_0	C	$(C–C_0)/C$	a (m)
Altitude	0.000	0.077	1.000	9000
Aspect (cos)	0.050	0.101	0.505	6000
Forest type	0.110	0.156	0.295	9000
Soil unit	0.059	0.255	0.769	6000
Liming	0.148	0.254	0.417	9000
Grass cover	0.069	0.185	0.627	9000

area, together with the Ca_{tot} minima. These two areas with small Mg_{tot} content correspond to the areas with the largest S_{tot} and N_{tot} content. Total S content has the largest values in the upper parts of the mountains. Total N and C have similar distributions (maps not shown). The maxima of S_{tot}, N_{tot} and C_{tot} were found in the centre of the western half of the area. This area corresponds to the windward side of the Jizerské Mountains (see the relief map on Figure 1), which causes the highest load of acidificants. Another area of relatively high S_{tot} and N_{tot} can be detected in the east. This may be attributed to specific air convection in the area affected by terrain. Sulphur in the forest floor is accumulated mainly in organic forms (Prietzel et al. 2004); it is supported by a similarity between S_{tot} and C_{tot} distribution. The best humus quality was, according to the lowest A_{400}/A_{600} ratio values, in the upper parts of the mountains, in the eastern and central parts of the region (map not shown). Humus of moderately better quality was thus found in the areas with large C_{tot}, S_{tot} and N_{tot} contents. It may be the result of grass cover on the clear-cut immission areas after forest decline (Mládková et al. 2004, 2005).

Distribution of the lowest Al_{KCl} values corresponds to the highest pH values (Figure 2). The largest Al_{KCl} values are related to S_{tot}, N_{tot} and C_{tot} maxima. Sulphur deposition, as the main factor responsible for large geographical differences in acidity in forest soils, was shown in Sweden by Karltun (1994). Organic C may be accumulated in the forest floor, beside other reasons, due to an elevated Al content (Mulder et al. 2001, Schwesig et al. 2003). The ratio S/Ca exhibits a similar distribution as Al_{KCl}, as well as S/(Ca + Mg) (map not shown). It implicates that the content of potentially toxic Al is controlled by the balance between acidifying compounds and base soil components. It corresponds to Evans et al. (2000) who showed a relationship between site acidity and the balance between Ca and Mg cations and sulphate.

Effect of stand factors on spatial distribution of soil characteristics

Variogram parameters of stand factors are summarised in Table 2. Most stand factors showed medium spatial dependence with the ratio $(C–C_0)/C$ between 0.25 and 0.75 (Cambardella et al. 1994). Altitude and soil unit showed even a strong spatial dependence. The stand factors are certainly not completely independent. On the contrary, there are fairly strong spatial relationships of altitude with soil unit, liming, and grass cover, with structural

Table 3. Structural correlation coefficients between stand factors

Factor	Altitude	Aspect (cos)	Forest type	Soil unit	Liming	Grass cover
Altitude	1.000					
Aspect (cos)	–0.394	1.000				
Forest type	–	0.245	1.000			
Soil unit	0.781	–	–	1.000		
Liming	0.742	–0.199	–0.806	0.430	1.000	
Grass cover	0.741	–0.369	–0.904	0.590	0.361	1.000

Table 4. Structural correlation coefficients between the characteristics of the O horizon and stand factors

Characteristic	Altitude	Aspect (cos)	Forest type	Soil unit	Liming	Grass cover
Depth	0.806	–	–0.626	0.556	0.618	0.832
pH_{H_2O}	0.581	–	–	–	–	–
pH_{KCl}	0.818	0.203	–	–	–	–
A_{400}/A_{600}	–	–0.352	–	–0.678	–	–0.323
Mg_{tot}	–0.622	0.224	0.997	–0.577	–	–0.750
Ca_{tot}	–	–0.634	–	–0.202	0.996	–
C_{tot}	0.474	–	–0.819	–	0.587	–
S_{tot}	0.505	–	–0.877	0.113	–	0.185
N_{tot}	0.646	–	–0.840	–	0.583	0.309
Al_{KCl}	–0.237	0.063	–0.279	–	–0.991	–
Al_{CuCl_2}	0.886	–	–	–	–	0.919
$Al_{Na_4P_2O_7}$	0.601	–	–	0.538	–	0.672
S/Ca	0.221	0.266	–0.573	0.396	0.162	–
S/(Ca + Mg)	0.475	0.936	–0.956	0.429	–	0.376

correlation coefficients higher than 0.7 (Table 3). It can be easily explained since Podzols developed mainly in the highest altitudes, while Cambisols are distributed in lower positions. Upper parts of the mountains were most influenced by atmospheric deposition and forest decline, so that liming was focused on these areas. Grass cover spread also at the highest altitudes, as it was already mentioned. However, the limed area is not the same as the area with grass cover, though they overlap. Forest type is a factor influenced by man because the current forest composition is not natural. Spruce forest covers most of the region, irrespective of the altitude, while beech forest remained only on several rather small areas. No spatial relationship between forest type and altitude was therefore found. In contrast, forest type showed a strong inverse spatial relationship with liming and grass cover. It is due to the fact that liming was applied almost exclusively on spruce forest, and grass spread mainly in the areas of declined spruce forest. It can be stated then that it is difficult to separate the effect of each particular factor.

Structural correlation coefficients of the relationship between soil properties and stand factors revealed some interesting results (Table 4). Selected crossvariograms are shown in Figure 3. Increasing depth of organic horizons with increasing altitude suggests slower rate of organic matter decomposition probably due to lower temperature and potentially also due to lower litter quality. Altitude also showed positive structural correlation coefficients for both types of pH, C_{tot}, S_{tot}, N_{tot}, content of both types of organic Al (Al_{CuCl_2} and $Al_{Na_4P_2O_7}$), and the ratio S/(Ca + Mg). Inverse spatial relationship was found between altitude and Mg_{tot}; low negative coefficient was found also between altitude and Al_{KCl}. It can be summarized that in high altitudes, there is high S and N deposition and the smallest Mg_{tot} content. However, there is also the highest pH and more Al is bound in organic forms than in exchangeable forms. The structural correlation coefficients of aspect indicate that the highest ratio S/(Ca + Mg) is on the slopes with northern exposition, where the Ca_{tot} content is the lowest. Sulphur content did not show any spatial correlation with the cosine of the aspect. As most acidificants were brought to the region with western winds, some relationships with sine of the aspect stressing the direction east-west could be expected. No spatial dependence of aspect sine was however found, so that its spatial relationship with soil properties could not be explored. Forest type provided positive values of structural correlation coefficient for Mg_{tot} and negative values for horizon depth, C_{tot}, S_{tot}, N_{tot}, Al_{KCl}, S/Ca, and S/(Ca + Mg). It means a smaller depth of the forest floor under beech, a smaller accumulation of organic carbon and acidifying substances, and a larger amount of Mg_{tot}, compared to the forest floor under spruce. It corresponds to results reported by Rothe et al. (2002). It can be explained by the

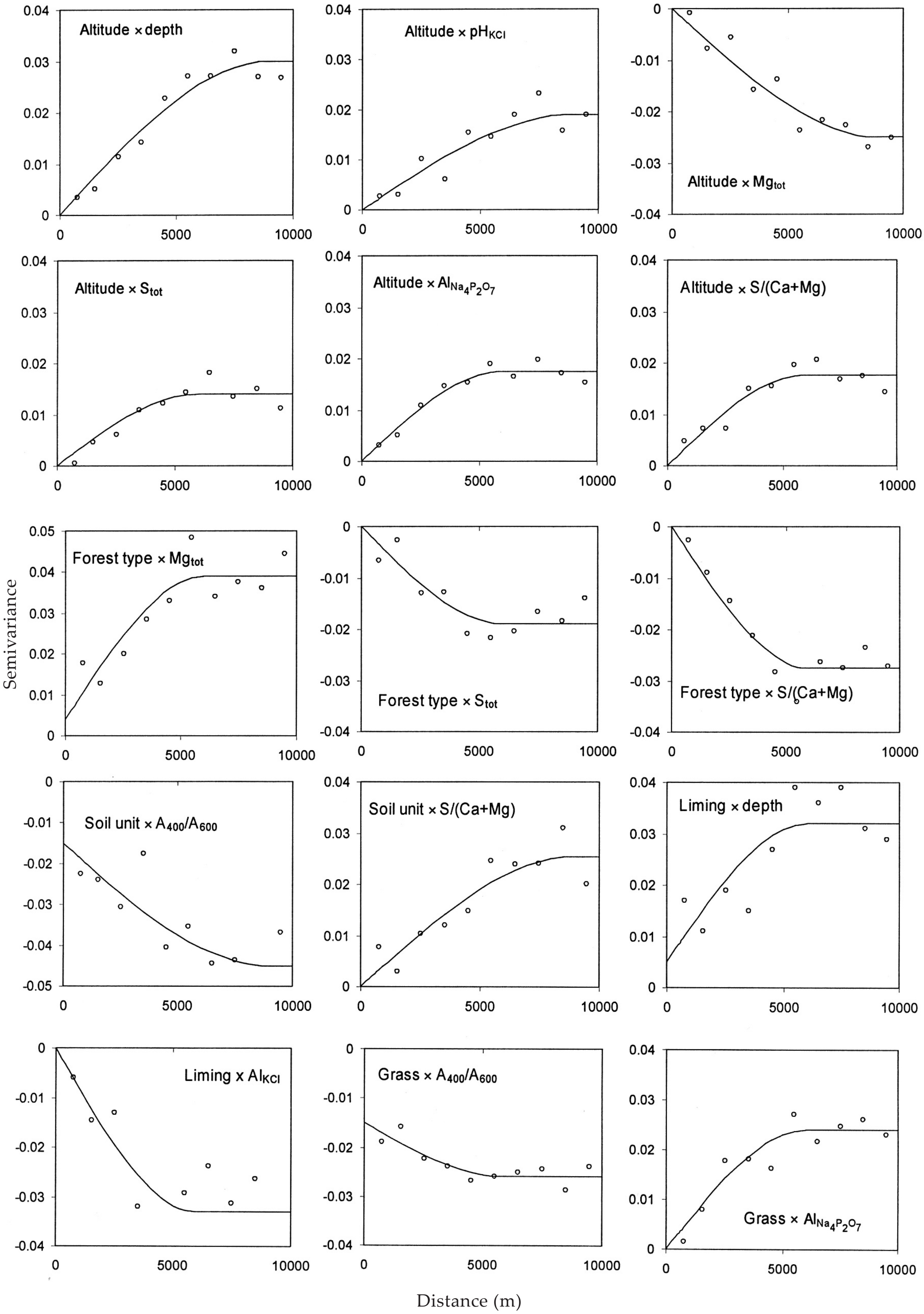

Figure 3. Selected crossvariograms describing spatial relationship between soil characteristics and stand factors (standardized values)

type of litter from beech as broadleaved species, and by a smaller interception of dry deposition by beech trees. Higher content of potentially mobile Al forms under spruce forest compared to mixed forest was shown by Brandtberg and Simonsson (2003). Nevertheless, the effect of position of beech forests at lower altitudes of the Jizerské Mountains region with smaller loads of acidifying substances cannot be omitted, either.

Positive coefficients of soil unit were found for horizon depth, $Al_{Na_4P_2O_7}$, and the ratios S/Ca and S/(Ca + Mg); negative coefficients for A_{400}/A_{600}, Mg_{tot}, and Ca_{tot}. It implicates a larger accumulation of organic matter in Podzols compared to Cambisols; a more important Al binding to this organic matter; and a smaller content of Mg_{tot} and Ca_{tot}. Yet, soil organic matter quality assessed by the A_{400}/A_{600} ratio appeared generally better in Podzols than in Cambisols. Liming provided positive coefficients for horizon depth, Ca_{tot}, C_{tot}, and N_{tot}, and negative coefficient for Al_{KCl}. It is therefore apparent that liming increased Ca content in soils, at least in the surface organic horizon, and decreased concentration of potentially toxic Al_{KCl}. Increased mineralization after liming was not confirmed by these data; on the contrary, limed areas showed generally deeper organic horizons and larger C_{tot} content. There are two possible explanations. First, humus layer could recover since the 1980's when the liming was applied. Nonetheless, Jandl et al. (2003) found reduced C pool in the litter layer even 20 years after limestone application. Second, liming was applied at high altitudes with deep O horizon and the increased mineralization did not reduce the horizon depth as much as to the values common in lower altitudes. It should be however noticed that the data concerning the extent and doses of liming in the past are not too precise. Grass cover provided positive structural correlation coefficients for horizon depth, N_{tot}, Al_{CuCl_2}, $Al_{Na_4P_2O_7}$, and the ratio S/(Ca + Mg). Negative coefficients are shown for A_{400}/A_{600} and Mg_{tot}. It could indicate that the grass cover improves the quality of organic matter, which leads to larger Al binding, even if it is in the areas with the lowest Mg content and the highest S and N deposition. Grass cover can thus improve soil chemical conditions, at least temporarily, which may help forest restoration on the immission clearcut areas. However, the grass cover aggravates planting and establishment of new trees.

It can be concluded that the spatial distribution of soil acidification is a complex process controlled by an interaction of a number of stand factors. Relief, soil unit, forest or herbaceous vegetation, and liming appeared to be the most important factors of forest floor properties; local geology is not supposed to play an important role in spatial variation of the forest floor properties in the Jizerské Mountains because it is rather uniform in this region. Nevertheless, it is difficult, if not impossible, to clearly separate the effect of each particular factor because they are mutually related. The level of acidification can be assessed by the balance between acidifying compounds and base components, i.e. by the ratio S/Ca or S/(Ca + Mg).

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ABSTRAKT

Faktory prostorového rozložení vlastností organických horizontů lesních půd Jizerských hor

Cílem tohoto příspěvku je zhodnotit prostorové rozložení půdních charakteristik nadložních horizontů lesních půd na území Jizerských hor a posoudit vliv stanovištních faktorů (nadmořské výšky, expozice, druhu porostu, půdního typu, vápnění a porostů třtiny) s využitím geostatistických metod a prostorových korelačních koeficientů. Většina půdních charakteristik vykázala slabou prostorovou závislost s rozsahem variogramu 6000 m. Byly vytvořeny krigingové mapy prostorového rozložení půdních charakteristik. Většina charakteristik byla ovlivněna nadmořskou výškou. Byl potvrzen obecný pokles hodnot pH a obsahu Ca a Mg a zvýšení obsahu potenciálně toxických forem Al (Al_{KCl}) při vysoké depozici S a N, zvýšení pH a snížení obsahu Al_{KCl} v důsledku vápnění, a dále vyšší hodnoty pH a obsahu Mg a nižší koncentrace Al_{KCl} pod bukovými porosty. Ve vyšších polohách pod porosty třtiny chloupkaté (*Calamagrostis villosa*) byla však i přes relativně vysoké obsahy S a N zjištěna nižší kyselost a kvalitnější organická hmota. Poměry S/Ca a S/(Ca + Mg) mohou sloužit jako indikátor míry acidifikace půdy.

Klíčová slova: acidifikace půdy; prostorové rozložení; stanovištní faktory; lesní půdy; geostatistika

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