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SOIL COMPONENT VECTORS IN THE SOUTHWESTERN SILESIAN BESKIDS

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ABSTRACT

The soil is an irreplaceable ecological factor in forests where it participates in the nutrition of tree species and in their overall health status. Whether the predisposition roles of soils are manifested as multivariate sets of mutually interacting variables was tested on examples of the multivariate evaluation of properties of forest floor, top-soil and diagnostic horizons in the area of the Silesian Beskids afflicted by the decline of spruce stands. The material was collected in eleven selected spruce, spruce-beech and beech stands where samples of Cambisols, Podzols and Stagnosols were taken. Using the principal component analysis (PCA) we compared soil pH, passive parts of the sorption complex from extraction in $BaCl_2$, soil carbon and nitrogen, total element contents and hydrophysical properties in the particular horizons. Factor analysis separated mutually correlative subsets (d) from the spectrum of variables. Component weights were transformed to d-dimensional vectors (***CV***). For each vector its angular deviation from the central plane was determined. The goniometric relation $|\boldsymbol{CV}|/\sin\alpha$ made it possible to compare the variables of horizons in factor planes by the analysis of variance. The synergies of three multivariate factors were found out. In the forest floor the pedomorphic factor set based on the characteristics of litterfall is the most important. In mineral horizons the roles of mineral-predisposition and hydrophysical factors are also significant. Differences in cation exchange capacity, total carbon and total iron cause the relatively largest permanent differences among the investigated horizons and probably reflect the overall spatial diversity of soil units in the area concerned.

Key words: PCA, vector, forest soil, soil ecology, pedomorphic factors

INTRODUCTION

The soil is an irreplaceable component of ecological factors in forests. It consists of three organized spheres: solid component, liquids (soil solution) and gases, which are in incessant interactions. Solid phases comprise non-living particles of different size, of inorganic and organic origin. Large particles disintegrate to smaller ones, are subjected to chemical dissolution, weathering and gravitational translocation. Besides disintegration various residues of soil matter are united to form aggregates by covalent and van der Waals bonds. Soil clay has the greatest importance for interactions with the other soil spheres. Soil clay particles are of colloidal character; it means that they are amphoteric and have an ion-exchange capacity. The soil solution is a micro-heterogeneous system containing not only dissolved mineral salts but also free colloids. These dispersed colloids are composed of colloidal humus, clayey weathering products, proteins and bacteria. The soil air has a different ratio of gases from that of the free atmosphere. It has a high content of water vapours that often pass from liquid phase to gaseous phase, regularly influencing the soil solution consistency.

Nonlinear multivariate models are used to objectively describe relations among different groups of soil properties [14]. Linear models are able to describe only a part of relations corresponding to the function defined in advance. They separate other components as residua not satisfying the model but influencing its probability.

The majority of the non-linear models are based on the principle of expressing different spatial or correlative dimensions. The computation of dimensionality of the observed system makes it possible to compare groups of variables influenced by the same number of factors without the manifestation of residual components. Especially the principal component analysis (PCA) is designed to investigate relations among ecological data that are often susceptible to non-homogeneous variances [10]. Different modifications of PCA are usually aimed at a description of differences among the studied systems. In landscape ecology PCA defines the territory as a function of soil management in which it identifies significant characterizing parameters [18]. In our case study we focused on multivariate evaluation of operational soil analyses in the area of the Silesian Beskids afflicted by the decline of spruce stands [6]. The objective of the present study was to describe multivariate factors predisposing the condition of forest soils.

MATERIAL

In 2007–2008 a soil survey was conducted in spruce, spruce-beech and beech forests on southwestern slopes of the Silesian Beskids (Table 1). In total 11 forest stands (from beech to fir-beech altitudinal zone; 530–811 m a.s.l.) were selected where three sampling points were evenly selected on an area of 900 m^2 in diagonal direction down the slope. At each sampling point samples of humification organic horizon (OH), top-soil horizon (TSH) and diagnostic horizon (DH) were separated. The collected material comprised 33 dug holes and 99 soil samples. A dominant soil type [9] is presented for each investigated stand. The form of forest floor is described by taxonomic classification [4].

Table 1. Basic characteristics of the investigated forest stands (generalized after [12])

Plot	WGS 84 coordinates		Altitude (m)	Exposition	Leading soil type	Humus form	Stand composition
	N	E					
1	49,572	18,832	600	E	Haplic Cambisol	Hemimor	spruce
2	49,586	18,830	749	S	Entic Podzol	Hemimor	spruce
3	49,669	18,785	678	N	Skeletic Cambisol	Mormoder	Beech/spruce
4	49,663	18,801	600	E	Skeletic Cambisol	Mormoder	Spruce
5	49,509	18,639	730	E	Skeletic Cambisol	Mormoder	Spruce
6	49,513	18,611	786	N	Dystric Cambisol	Mormoder	Spruce
7	49,512	18,661	811	W	Haplic Cambisol	Mormoder	Spruce
8	49,619	18,799	760	NE	Haplic Cambisol	Mormoder	Spruce/ahs
9	49,629	18,801	626	W	Dystric Cambisol	Humimor	Beech/spruce
10	49,649	18,766	530	NE	Haplic Cambisol	Vermimull	Beech/spruce
11	49,616	18,681	538	E	Dystric Stagnosol	Mullmoder	Beech

These characteristics were determined in TSH and DH: wet bulk density (D_w) determined gravimetrically, bulk density (D_d) determined from a sample dried to constant weight, specific density (D_s) determined pycnometrically, aeration (A), total porosity (P), maximum capillary capacity (MCC), retention water capacity (RWC), minimum air capacity (A_{MCC}), saturation ratio (R_{ps}) and relative capillary moisture (R_v) determined from samples of natural soil in metal core cylinders of the uniform volume 100 cm^3. Particle-size fractions of sand (2–0.1 mm), silty sand (0.1–0.05 mm), silt (0.05–0.01 mm), very fine silt (VFS) (0.01–0.002 mm) and clay (< 0.002 mm) were subjected to quantitative determination, oxidizable carbon (C_{ox}) was determined according to ISO 10694 and total soil nitrogen (N_t) according to Dumas [24], total phosphorus (P_{tot}), calcium (Ca_{tot}), magnesium (Mg_{tot}), potassium (K_{tot}), iron (Fe_{tot}) and manganese (Mn_{tot}) by extraction in aqua regia. Potentially available macrobiogenic metals were assessed photometrically by Mehlich 3 extraction [23]. Exchange base ions (Ca^{2+}, Mg^{2+}, K^+, Na^+) were determined by FAAS from an extractant in $BaCl_2$ at soil pH according to CSN ISO 11260. Exchangeable acid ions ($EAI = H^+ + Al^{3+} + Fe^{x+} + Mn^{x+}$) were determined by extraction in KCl and titration with NaOH to pH 7.8. As for the physicochemical soil properties, pH/H_2O, pH/KCl and variables of the passive part of the sorption complex were determined: base cation content (BCC), cation exchange capacity ($CEC = BCC + EAI$), BCC/Al^{3+} ratio and base saturation (BS):

$$BCC = \sum[c(Ca^{2+}), c(Mg^{2+}), c(K^{+}), c(Na^{+})]$$

$$BS = \frac{\sum[c(Ca^{2+}); c(Mg^{2+}); c(K^{+}); c(Na^{+})]}{BCC + \sum[c(H^{+}); c(Al^{3+}); c(Fe^{x+}); c(Mn^{x+})]} \cdot 100 = \frac{BCC}{CEC} \cdot 100$$

METHODS

Survey data analysis

The identified soil types and forest floor forms were described by pivot half-sums (P_L) and pivot ranges (R_L) of the particular properties [7]. Data on properties in separated soil horizons were tested by normality tests from the evaluation of peakedness (E_1) and skewness (A_1) with the critical value 1.96 [22].

Factor analysis

The identification of influential factors, accounting in total for > 50% of total variance, was done from Cattell's index graph [3]. The recognized number of influential factors was taken as the limit for further consecutive comparisons. Similarity/dissimilarity of the properties of sampling points was evaluated in a factor plane with variance expressed by the identified factors. Factor analysis (FA) separated subsets of variables depending just on one specific factor from the computation of loadings at $P>0.70$. Based on this limitation, specific designation of a concrete ecological factor was estimated. These factors are assumed to find expression in the ecology of investigated geobiocoenoses [5].

Modification of principal component analysis

The known number of influential factors according to FA was a necessary initial condition for the definition of admissible dimensionality of relations among the investigated soil variables. The determined minimum number of influential (ecological) factors was taken as an assumption of the minimum number of dimensions (d) for the transformation of component weights to component vectors ($|\boldsymbol{CV}|$). PCA reduces the number of values in compared variables from which virtual variables (principal components) are expressed. The dimension of traits and the variance of their values are diminished without any loss of information. Each principal component is a linear combination of original traits [11]. Component weights are defined in a factor plane by the position that is unambiguous in relation to the origin ($\boldsymbol{Y}_0[y_1;\ 0;\ y_3;\ \dots\ y_d]$) and other weights. Under this assumption the factor coordinates $Y[y_1;\ y_2;\ y_3;\ \dots\ y_d]$ of the particular weights were read off. Factor coordinates have the properties of vector identificators in a virtual d-dimensional space. Their transformation to $|\boldsymbol{CV}|$ was done by the Euclidean function:

$$|\boldsymbol{CV}|_n = \sqrt{y_{n1}^2 + y_{n2}^2 + y_{n3}^2 + \dots y_{nd}^2}$$

The deviation of component vector (a) from the plane of the origin $\boldsymbol{Y}_0[y_1; y_2; y_3]$ was computed by the function:

$$a_n = \frac{y_{n1} \cdot y_1 + y_{n2} \cdot y_2 + y_{n3} \cdot y_3}{|\boldsymbol{CV}|_n \cdot |\boldsymbol{Y}_0|}$$

The known angle between two planes, one of which has an unambiguously defined dimension, enables to construct a virtual triangle according to the edge-angle-edge (*eae*) theorem. An important condition is that the operating virtual space is Euclidean space, so that it has a coordinate origin and orthogonal coordinates. Thanks to it $\boldsymbol{Y}_0[y_1;\ 0;\ y_3]$, and therefore the deviation of the vector from the plane may be expressed as a deviation of two lines. Under these conditions the dimensions of the triangle may be defined by the law of sines. The ratio of $|\boldsymbol{CV}|/\sin a$ was computed as a parameter of the magnitude and correlative tendency of a variable in a virtual space. The parameters of $|\boldsymbol{CV}|/\sin a$ for the particular variables were mutually compared by parametric analysis of variance and Kruskal-Wallis test at $P<0.05$. Using the computation of $|\boldsymbol{CV}|_n$ not only potential differences among the soil variables in separated horizons were expressed but also differences among the sampling points were described.

3D projection

3D projection of variables was done by RGL. RGL is a shared library of the statistical programme R [21] which is an interface for 3D objects of the graphical tool OpenGL (Open Graphics Library) [1]. RGL contains a number of functions that make it possible to draw a high amount of primitives (e.g. point, lines, plane, surface) and to define the basic environment for visualization of graphs (setting and plotting of texts, axes, symbols).

Our visualization is based on the principle that it works with vectors defined by the extreme values of the coordinates in Euclidean space in which the origin at point [0;0;0] is known. The function *rgl.points()* is used for the projection of points, expecting parameters with coordinates XYZ at its entry. Points were visualized by the function *rgl.lines()*, assuming the entering of a line defined by two extreme points [8]. The first of this pair is the point of origin of the coordinate system and the second is the point with the values of the studied component variable.

RESULTS AND DISCUSSION

Multivariate analyses

The character of distribution of soil variables is regulated by two dominant factors only in the forest floor. In lower horizons the boundary of 50% biased variance is exceeded when three factors are included simultaneously. Cattell's index graphs explicitly document that in the forest floor there is also a clear-cut boundary between the influence of the first and second factor (Fig. 1). The low distinctness of detected soil factors in mineral horizons is a reason why it is necessary to consider their higher number for a sufficient inclusion of data variability. The final effect of this situation is that the dimensionality of mineral horizons is higher than the dimensionality of forest floor. Such a situation is also caused by a higher number of variables determined from the analyses of mineral horizons. They were hydrophysical variables and texture. No comparisons of dimensionality of the studied soil horizons from the same numbers of variables were made for the needs of this study. The minimum applied dimensionality was based on three factors.

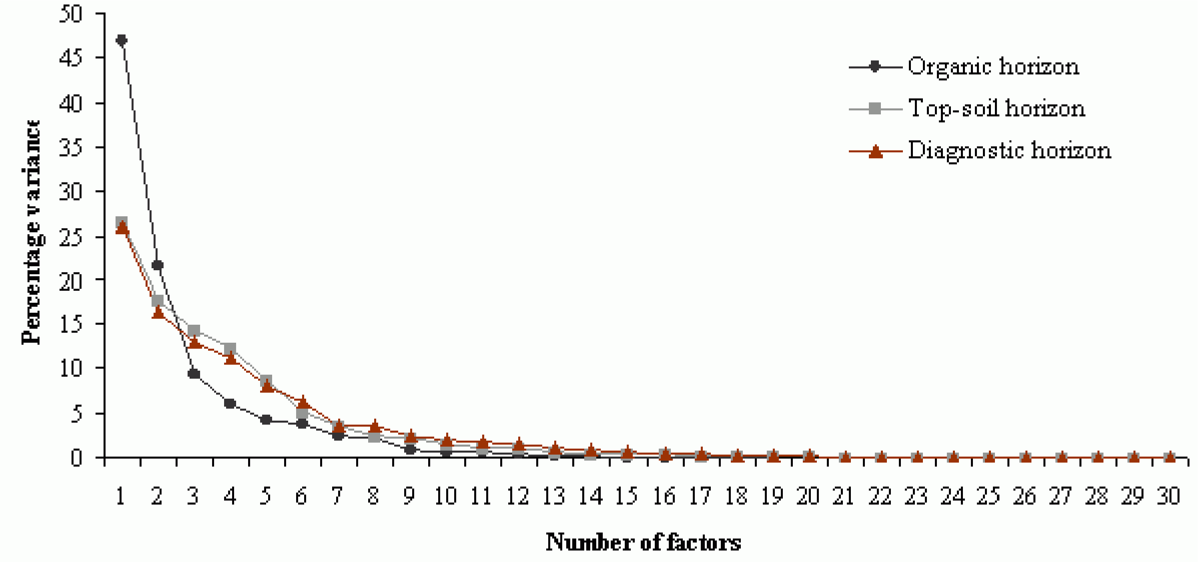

Fig. 1. Cattel's index graph of multidimensional variance distribution in properties populations of organic, top-soil and diagnostic soil horizons

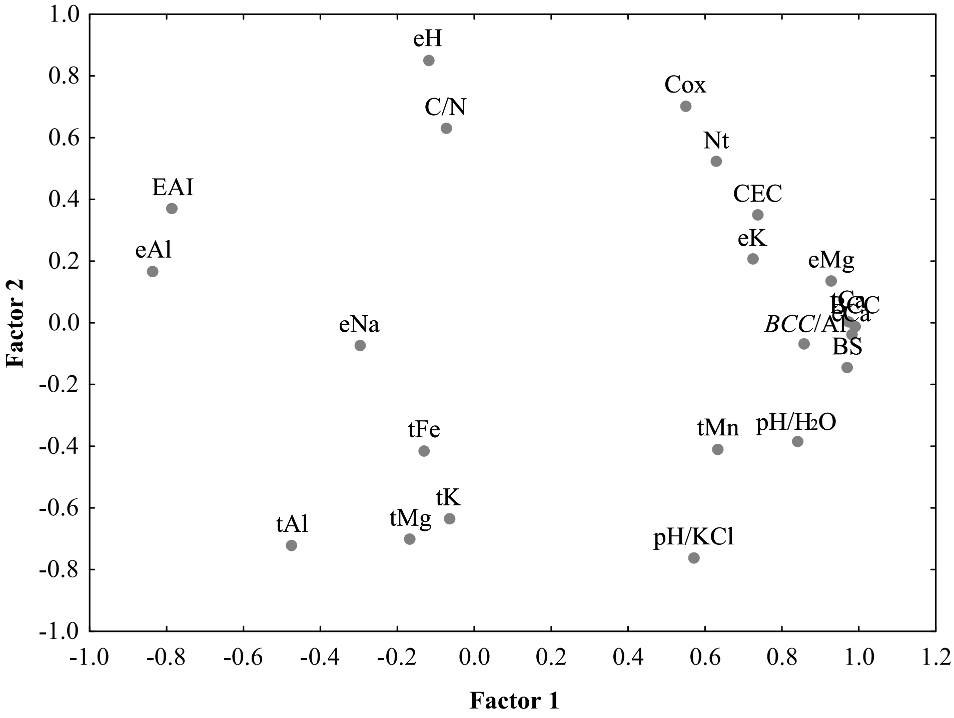

Fig. 2. Factor analysis among chemical properties in sampled soil organic horizons (for explaination of the qualities see table 3)

These influential factors were arranged at hierarchical levels according to the included variability of soil variables (Table 2). A subset of pedomorphic factors (factor 1) is the most important, which is reflected in the distribution of the values of soil reaction, Ca^{2+}, exchange base content, base saturation and *BCC*/Al ratio in the whole soil profile. The variables of the pedomorphic factor subset can explain up to 99.39% of variability in the evaluated data of the whole soil profile. In OH they explain 48.87% of variability (Fig. 2), in TSH 26.56% (Fig. 3) and in DG 25.95% of variability (Fig. 4). The similarity of the explained variability of data in mineral horizons is apparent: its higher value in the forest floor is a result of the undisputable influence of tree species on its properties. The other factor subsets are less important. The subset of predisposition factors (factor 2) comprised pH/KCl and C_{ox} in the forest floor and e.g. Al_{tot} and Mg_{tot} simultaneously in the forest floor and DH. Contents of iron and potassium acted as influential variables in diagnostic horizons only. *CEC* is the most important predisposition variable in TSH. The set of these variables is mainly connected with permanent soil conditions given by the soil-forming substrate. Contents of soil aluminium and magnesium may influence the decline of spruce stands [6; 20]. The sensitivity of different soils to acidification is associated with their predispositions to forest decline. Soils in some areas can participate in the origin of total ecological limits of sites [16]. Their manifestation is enhanced by drought.

Table 2. The factor analysis of quantities distribution in separated soil horizons. Factor loadings are detected at *P*>0.70 (bold)

Quantity	Factor 1			**Factor 2**			**Factor 3**		
	OH	TSH	**DH**	**OH**	**TSH**	**DH**	**OH**	**TSH**	**DH**
pH/H_2O	**0.84**	**-0.92**	**-0.80**	-0.38	0.20	0.33	0.00	0.09	0.18
pH/KCl	0.57	**-0.84**	-0.47	**-0.76**	0.17	0.52	0.03	-0.13	0.06
C_{ox}	0.55	0.13	0.25	**0.70**	-0.48	0.41	0.38	0.67	0.08
N_t	0.63	-0.03	0.05	0.52	-0.53	0.52	0.44	0.69	-0.14
C/N	-0.07	0.61	0.42	0.63	0.20	-0.32	0.00	0.00	0.41
Ca^{2+}	**0.98**	**-0.83**	**-0.81**	-0.04	0.30	0.20	-0.03	0.34	0.04
Mg^{2+}	**0.93**	-0.56	-0.58	0.14	-0.12	0.28	0.05	0.66	0.00
K^+	**0.72**	-0.39	0.20	0.21	-0.45	0.50	0.25	0.66	-0.36
Na^+	-0.30	0.22	-0.09	-0.07	-0.61	-0.16	0.04	0.20	0.24
BCC	**0.99**	**-0.82**	**-0.79**	-0.01	0.23	0.23	-0.01	0.40	0.02
CEC	**0.74**	0.23	0.61	0.35	**-0.72**	0.39	0.41	0.32	-0.15
BS	**0.97**	**-0.84**	**-0.88**	-0.14	0.36	0.13	-0.10	0.27	0.05
EA	**-0.79**	0.61	**0.79**	0.37	-0.68	0.27	0.42	0.03	-0.14
H^+	-0.12	0.60	0.43	**0.85**	-0.35	-0.22	0.29	0.35	0.24
Al^{3+}	**-0.84**	0.54	**0.78**	0.17	-0.67	0.29	0.39	-0.04	-0.16
BCC/Al	**0.86**	**-0.85**	**-0.79**	-0.07	0.35	0.17	-0.10	0.15	0.01
tFe	-0.13	-0.42	0.34	-0.41	-0.61	**0.77**	**0.72**	0.44	-0.11
tAl	-0.48	-0.31	0.07	**-0.72**	-0.51	**0.84**	0.30	-0.10	-0.06
tMn	0.63	-0.66	-0.08	-0.41	-0.23	0.45	0.35	0.19	-0.32
tCa	**0.97**	**-0.82**	-0.69	0.01	0.08	0.34	0.01	0.35	-0.01
tMg	-0.17	-0.40	-0.04	**-0.70**	-0.61	**0.71**	0.53	0.12	0.00
tK	-0.07	-0.17	0.23	-0.63	-0.48	**0.75**	0.21	0.08	-0.35
sand		0.55	0.54		0.35	-0.60		0.08	-0.08
Silty sand		0.12	-0.08		-0.05	0.56		-0.05	0.20
silt		-0.34	-0.35		-0.49	0.19		0.16	0.20
Very fine silt		-0.55	-0.52		0.14	0.26		-0.42	-0.19
clay		0.05	0.01		0.24	0.28		-0.03	-0.19
D_s		-0.25	0.01		-0.49	0.08		-0.19	**-0.83**
D_w		-0.43	-0.50		-0.54	-0.36		-0.58	**-0.70**
D_d		-0.32	-0.30		-0.53	-0.37		-0.45	**-0.85**
MCC		-0.05	-0.21		0.21	0.02		-0.08	**0.83**
RWC		-0.18	-0.35		0.09	0.05		-0.26	**0.75**
P		0.32	0.33		0.51	0.39		0.47	**0.82**
A		0.44	0.69		0.39	0.30		0.62	0.15
A_{MCC}		0.42	0.69		0.36	0.40		0.62	0.06
R_v		-0.36	-0.49		-0.32	0.10		-0.56	0.00
R_{ps}		-0.41	-0.69		-0.32	-0.17		-0.54	0.08

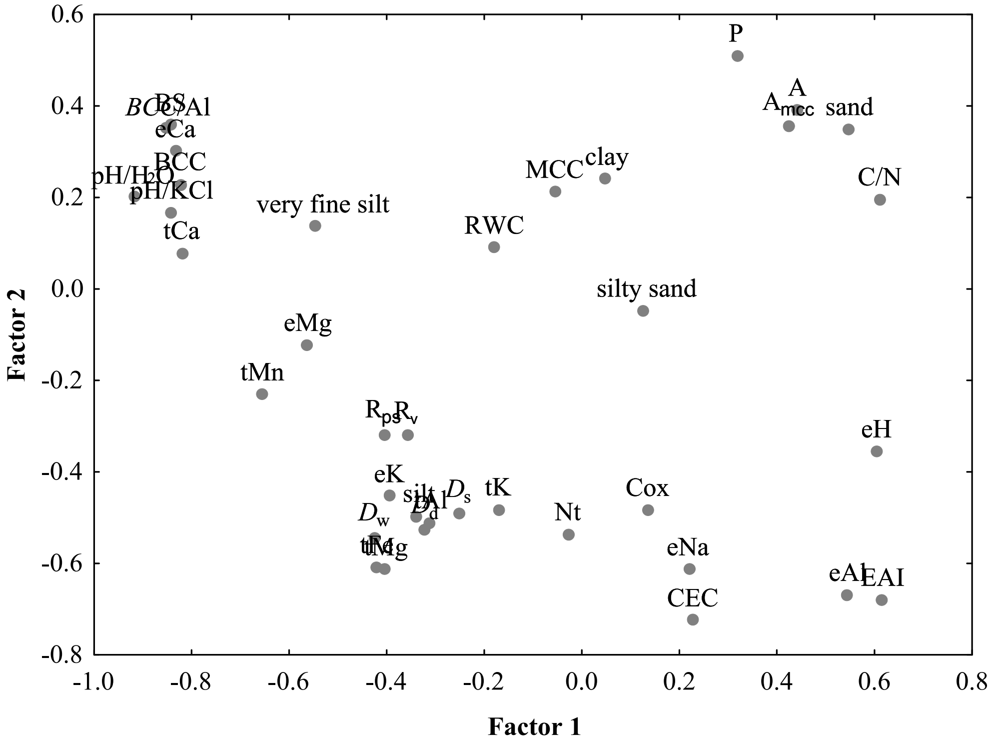

Fig. 3. Factor analysis among physical and chemical properties in sampled top-soil horizons (for explaination of the qualities see table 4)

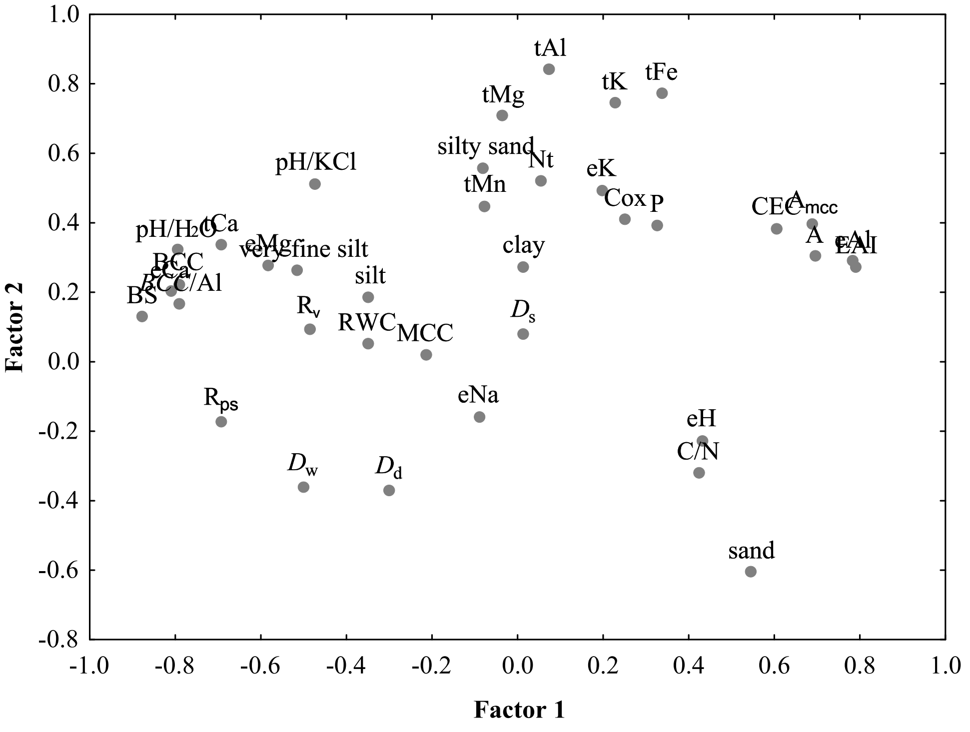

Fig. 4. Factor analysis among physical and chemical properties in sampled diagnostic soil horizons (for explaination of the qualities see table 5)

The set of predisposition factors from all investigated soil horizons may cover up to 55.51% of data variability. In OH it explains 21.61% of variability, in SH 17.62% and in DH 16.30% of variability. The third subset of soil factors corresponds to hydrophysical variables of diagnostic horizons (factor 3). It is a hydrostatic subset of soil-forming factors while volume and specific densities, *MCC*, *RWC* and soil porosity are their resultant. The set of hydrostatic factors from all investigated soil horizons covers only 36.6% of variability. In O-horizons it explains 9.32% of variability, in TSH 14.29% and in DH 12.99% of variability.

The specification of the influence of tree species was reflected to the greatest extent in localities with the occurrence of vermimull, which had largely different sorption properties from the others. Localities with mullmoder were the most similar to vermimull by their chemical properties but they did not reach so high values of the content of carbon, nitrogen, magnesium and potassium. On the contrary, both vermimull and mullmoder had higher calcium contents, pH values, *BCC*, higher *BCC*/Al^{3+} ratio and lower contents of Al^{3+} (Table 3).

Table 3. Average ± 95% standard deviations of analyses soil properties in the observed humus forms. C_{ox} – total soil carbon (%); N_t – total soil nitrogen (%); R^{n+} – concentrations of exchangeble cations (cmol$^+$/kg); *BCC* – base cation content (cmol$^+$/kg); *CEC* – cation exchange capacity (cmol$^+$/kg); *BS* – base saturation (%); *EA* – exchangeable acidity (cmol$^+$/kg); tR – contents of total metal oxides (g/kg)

Quantity	Hemimor	Huminor	Mormoder	Mullmoder	Vermimull
pH/H_2O	3.74±0.32	3.77±0.10	3.75±0.22	4.14±0.73	4.24±0.50
pH/KCl	3.05±0.24	2.96±0.25	3.08±0.22	3.30±0.64	3.28±0.44
C_{ox}	21.76±12.07	23.76±10.72	31.20±13.58	26.25±18.16	39.26±2.73
N_t	1.01±0.44	0.96±0.58	1.31±0.33	1.14±0.66	1.72±0.20
C/N	22.55±4.10	25.40±4.20	22.05±5.10	24.30±6.20	22.65±1.50
Ca^{2+}	3.03±1.52	2.49±0.82	3.96±2.26	7.99±6.07	17.09±14.65
Mg^{2+}	0.56±0.33	0.49±0.19	0.90±0.49	1.04±0.43	1.91±0.65
K^+	0.53±0.18	0.50±0.21	0.78±0.44	0.71±0.29	1.79±0.45
Na^+	0.13±0.20	0.10±0.04	0.22±0.21	0.09±0.08	0.09±0.01
BCC	4.29±1.67	3.58±1.18	5.78±3.22	9.79±6.48	20.71±14.71
CEC	16.72±3.28	21.63±2.90	22.44±6.42	21.43±6.40	28.42±7.25
BS	25.90±14.20	16.85±7.70	25.20±9.20	49.90±43.20	70.75±33.70
EA	12.28±4.46	18.05±4.08	14.81±2.61	10.89±11.39	7.71±7.46
H^+	2.305±1.19	3.38±1.51	3.12±1.85	2.12±2.46	2.89±2.19
Al^{3+}	10.12±3.00	14.68±5.59	12.80±1.17	8.97±8.60	4.82±5.26
Fe_{tot}	25.2±9.80	39.30±11.6	47.85±25.70	27.40±14.6	31.35±12.7
Al_{tot}	15.25±2.90	23.20±16.6	18.65±8.50	17.70±8.00	10.95±2.5
Mn_{tot}	0.26±0.19	0.30±0.18	0.58±0.12	0.35±0.31	1.06±1.00
Ca_{tot}	1.30±0.60	0.95±0.30	1.65±0.50	2.95±1.90	5.85±4.30
Mg_{tot}	1.40±0.40	2.10±0.80	2.15±1.10	1.70±0.80	1.65±0.30
K_{tot}	1.20±0.20	1.25±0.30	1.55±0.30	1.65±0.50	1.50±0.20
BCC/Al	0.44±0.29	0.26±0.18	0.43±0.25	1.66±2.27	7.30±11.02

The factors of soil-forming substrates play a dominant role in the properties of top-soil horizons similarly like in the properties of diagnostic horizons. Total contents of elements usually demonstrate the chemical homogeneity of soil-forming substrates while differences in specific densities document local differences in the soil-forming matrix. The highest values of pH, Ca^{2+} and also of Ca_{tot}, Mn_{tot}, *BCC* and *BS* were determined in Stagnosols. Very similar concentrations of Mg^{2+} were found out in Dystric Stagnosol and Dystric Cambisol. The values of *EAI*, H^+ and Al^{3+} were markedly lower in Dystric Stagnosol than in the other soil types. Analogically, the *BCC*/Al^{3+} ratio reached an optimum level in Dystric Stagnosol. The highest contents of C_{ox} and N_t were measured in Haplic Cambisols and Haplic Podzols. D_w and D_d were quite similar in different soil types; moderately higher values of *MCC* and *RWC* were recorded in Stagnosols while in Cambisols these parameters reached the lowest values. Larger differences in physical conditions of soil bodies were observed in the aspects of pore aeration and saturation. The largest differences in physical conditions were found out between sampled Podzols and Stagnosols (Table 4).

Each of the investigated soil horizons is specific in the relations the sets of its properties maintain among each other. Therefore the effects of soil-forming factors are different not only in various soil units but also in the vertical direction of each soil profile. The relations among variables in the forest floor are strongly regulated by one factor only. It was documented by the clustering of the majority of sampling points in one quadrant of the factor plane. Similarly, samplings of TSH are assigned to one cluster while similar sampling points are outliers. Pedomorphic factors were indicated in both sets of mineral horizons in a very similar way but the variables influenced by predisposition and hydrophysical factors were recorded only in DH (Table 5).

Table 4. Average ± 95% standard deviations of analyses soil properties in mineral top-soil horizons of the observed soil types. C_{ox} – total soil carbon (%); N_t – total soil nitrogen (%); R^{n+} – concentrations of exchangeble cations (cmol$^+$/kg); *BCC* – base cation content (cmol$^+$/kg); *CEC* – cation exchange capacity (cmol$^+$/kg); *BS* – base saturation (%); *EA* – exchangeable acidity (cmol$^+$/kg); tR – contents of total metal oxides (g/kg); D_w – wet bulk density (g/cm^3); D_d – bulk density (g/cm^3); D_s – specific density (g/cm^3); *A* – aeration (%); *P* – total porosity (%); *MCC* – maximum capillary capacity (%), *RWC* – retention water capacity (%); A_{MCC} – minimum air capacity (%); R_{ps} – saturation ratio (%) and R_v – relative capillary moisture (%)

Quantity	Skeletic Cambisol	Haplic Cambisol	Dystric Cambisol	Entic Podzol	Haplic Podzol	Dystric Stagnosol
sand	29.71±6.65	31.99±15.39	37.85±12.50	42.64±0.71	40.66±16.87	26.45±3.50
silty sand	10.51±6.43	4.45±1.90	5.00±2.40	10.81±8.03	10.28±7.78	4.45±3.90
silt	41.09±9.62	45.27±26.45	37.60±28.00	34.49±8.42	37.13±6.07	44.55±5.10
very fine silt	13.56±5.47	9.45±5.50	11.49±9.01	9.99±0.81	10.26±2.33	21.30±4.20
clay	3.98±4.56	1.55±0.70	10.30±18.80	2.14±2.28	2.12±1.63	3.30±1.40
pH/H_2O	3.82±0.15	3.80±0.26	3.80±0.21	3.58±0.19	3.52±0.01	5.02±0.03
pH/KCl	3.39±0.18	3.06±0.37	3.11±0.26	3.04±0.28	2.91±0.05	3.97±0.05
Cox	5.13±1.55	11.83±6.86	7.42±4.74	8.32±4.61	8.55±8.04	6.23±1.68
Nt	0.28±0.07	0.58±0.47	0.36±0.35	0.41±0.08	0.36±0.30	0.37±0.09
C/N	18.95±3.50	22.45±5.50	23.30±9.60	19.90±7.40	23.10±3.00	17.00±0.40
Ca^{2+}	0.79±0.40	1.51±0.81	2.24±3.73	0.81±0.18	1.34±0.06	7.92±1.93
Mg^{2+}	0.21±0.11	0.34±0.24	0.37±0.52	0.18±0.04	0.22±0.15	0.64±0.26
K^+	0.21±0.06	0.32±0.15	0.22±0.22	0.18±0.01	0.22±0.18	0.39±0.19
Na^+	0.04±0.04	0.06±0.03	0.06±0.08	0.06±0.03	0.07±0.07	0.02±0.00
BCC	1.27±0.42	2.54±1.51	2.88±4.47	1.24±0.24	1.85±0.34	8.97±2.38
CEC	15.86±5.17	16.73±5.57	14.08±5.30	12.22±2.22	11.60±3.25	12.38±2.44
BS	7.05±1.90	13.30±7.00	18.55±28.70	10.15±0.10	16.05±1.50	72.20±5.00
EAI	14.67±4.64	13.90±4.82	12.53±5.40	10.98±1.98	9.76±2.91	3.41±0.06
H^+	0.94±0.37	2.25±1.40	1.39±0.81	1.65±0.46	2.05±1.11	0.22±0.05
Al^{3+}	13.55±4.70	11.60±3.58	11.04±5.25	9.34±2.44	7.71±1.80	3.19±0.01
Fe_{tot}	32.55±9.10	33.95±26.9	24.30±25.8	17.60±2.80	17.25±8.90	23.65±21.7
Al_{tot}	35.30±7.40	25.40±5.40	23.35±7.30	19.20±5.60	15.55±2.70	18.70±9.00
Mn_{tot}	0.34±0.26	0.31±0.37	0.11±0.10	0.09±0.01	0.12±0.08	0.55±0.94
Ca_{tot}	1.10±0.80	0.85±0.50	0.95±1.10	0.65±0.30	0.55±0.30	1.35±1.90
Mg_{tot}	3.50±0.20	2.65±1.30	1.90±1.00	1.50±0.80	1.15±0.30	1.70±1.40
K_{tot}	2.55±1.90	1.85±0.70	1.50±0.60	1.65±1.10	1.15±0.30	1.30±0.60
D_s	2.44±0.09	2.49±0.02	2.44±0.07	2.35±0.33	2.40±0.16	2.38±0.15
D_w	1.47±0.14	1.52±0.27	1.33±0.42	1.32±0.51	1.33±0.15	1.49±0.42
D_d	1.14±0.18	1.11±0.26	0.99±0.47	0.94±0.56	0.97±0.19	0.97±0.51
MCC	41.55±8.26	45.23±10.15	45.65±16.54	45.60±6.00	45.89±6.64	54.90±13.47
RWC	31.61±4.15	34.05±11.10	33.93±14.33	35.13±4.30	34.47±2.39	45.67±8.25
P	54.22±6.43	55.39±10.00	59.48±18.33	60.86±18.12	59.45±5.15	59.39±19.07
A	19.00±5.20	17.76±18.98	29.39±20.09	22.92±13.45	23.87±1.26	8.039±9.50
A_{MKK}	11.01±3.12	10.28±13.88	19.26±13.18	15.26±12.12	13.56±1.49	4.489±5.60
R_v	80.52±5.50	84.62±15.70	72.97±18.60	83.21±0.71	77.64±2.76	93.87±5.60
R_{ps}	64.44±6.79	69.45±33.90	49.59±23.91	63.16±11.14	59.81±1.36	87.42±11.96
BCC/Al	0.08±0.03	0.19±0.12	0.29±0.49	0.13±0.01	0.24±0.01	2.81±0.74

Table 5. Average ± 95% standard deviations of analyses soil properties in diagnostic horizons of the observed soil types. C_{ox} – total soil carbon (%); N_t – total soil nitrogen (%); R^{n+} – concentrations of exchangeble cations (cmol$^+$/kg); *BCC* – base cation content (cmol$^+$/kg); *CEC* – cation exchange capacity (cmol$^+$/kg); *BS* – base saturation (%); *EA* – exchangeable acidity (cmol$^+$/kg); tR – contents of total metal oxides (g/kg); D_w – wet bulk density (g/cm^3); D_d – bulk density (g/cm^3); D_s – specific density (g/cm^3); *A* – aeration (%); *P* – total porosity (%(; *MCC* – maximum capillary capacity (%), *RWC* – retention water capacity (%); A_{MCC} – minimum air capacity (%); R_{ps} – saturation ratio (%) and R_v – relative capillary moisture (%)

Quantity	Skeletic Cambisol	Haplic Cambisol	Dystric Cambisol	Entic Podzol	Haplic Podzol	Dystric Stagnosol
sand	24.90±6.20	35.45±24.70	38.45±11.70	42.41±3.78	37.50±10.00	15.65±1.50
silty sand	11.47±7.65	14.35±6.70	9.05±4.90	10.53±0.47	5.35±0.10	10.55±1.10
silt	36.06±8.92	34.35±14.30	33.50±4.40	26.33±13.53	36.30±15.80	38.60±0.20
very fine silt	16.76±4.73	12.75±4.10	15.10±2.20	11.64±2.70	17.65±3.30	26.25±0.70
clay	5.70±4.20	3.15±0.50	3.90±0.20	8.70±13.60	3.25±2.70	8.95±0.50
pH/H_2O	4.08±0.07	4.39±0.74	4.17±0.07	3.91±0.18	3.82±0.03	5.14±0.21
pH/KCl	3.74±0.13	3.75±0.88	3.58±0.40	3.57±0.06	3.51±0.19	3.74±0.17
Cox	2.73±0.95	1.78±1.53	1.83±0.33	2.71±0.99	1.89±1.90	1.09±0.46
Nt	0.16±0.06	0.10±0.06	0.10±0.04	0.14±0.08	0.11±0.08	0.08±0.03
C/N	16.85±1.50	17.65±7.30	19.85±11.70	19.95±4.30	16.15±5.50	14.50±0.40
Ca^{2+}	0.89±0.41	0.75±0.54	1.65±1.78	0.83±0.73	0.85±0.40	3.83±0.09
Mg^{2+}	0.12±0.04	0.09±0.04	0.19±0.28	0.12±0.13	0.07±0.06	0.32±0.06
K^+	0.14±0.07	0.10±0.05	0.12±0.14	0.09±0.05	0.07±0.02	0.15±0.06
Na^+	0.02±0.00	0.04±0.03	0.08±0.07	0.05±0.00	0.02±0.00	0.02±0.00
BCC	1.23±0.51	1.00±0.52	2.04±2.26	1.09±0.92	1.02±0.48	4.32±0.21
CEC	14.28±5.46	9.49±2.01	11.08±6.45	13.42±3.85	9.71±6.81	9.59±2.92
BS	7.25±5.90	11.00±5.40	20.85±25.70	7.80±4.60	10.95±2.70	45.90±11.80
EAI	12.81±4.94	8.34±1.75	9.71±6.91	12.33±2.93	8.69±6.32	5.28±2.71
H^+	0.34±0.17	0.34±0.22	0.60±0.74	0.45±0.01	0.40±0.07	0.18±0.03
Al^{3+}	12.31±5.16	8.00±1.82	9.11±6.16	11.89±2.92	8.29±6.25	5.11±2.73
Fe_{tot}	35.15±11.90	29.50±7.20	23.80±17.20	30.55±17.90	25.20±21.6	19.80±5.00
Al_{tot}	43.95±14.50	37.75±12.70	29.65±21.70	27.25±10.30	22.75±19.5	34.00±8.00
Mn_{tot}	0.46±0.16	0.39±0.35	0.16±0.19	0.13±0.10	0.13±0.10	0.43±0.28
Ca_{tot}	0.85±0.50	0.60±0.20	0.80±0.80	0.55±0.10	0.55±0.30	1.55±0.10
Mg_{tot}	4.35±0.70	3.95±2.10	2.55±2.50	2.00±0.80	1.85±1.90	2.65±0.50
K_{tot}	2.95±1.90	2.45±0.70	1.80±0.80	1.80±1.20	1.55±0.70	2.35±0.70
D_s	2.56±0.05	2.54±0.04	2.51±0.10	2.44±0.05	2.55±0.10	2.50±0.03
D_w	1.55±0.14	1.67±0.34	1.50±0.44	1.43±0.19	1.51±0.69	1.62±0.08
D_d	1.19±0.12	1.33±0.35	1.15±0.52	1.11±0.12	1.27±0.78	1.16±0.15
MCC	38.04±9.26	39.28±8.65	46.86±16.21	40.38±6.59	31.30±13.47	48.74±5.89
RWC	30.33±6.42	30.49±3.51	36.15±16.06	30.54±4.94	23.20±9.40	42.34±5.15
P	52.97±4.48	48.06±12.30	54.25±19.03	54.69±3.88	50.48±28.68	53.68±5.39
A	20.01±8.45	14.54±10.22	17.73±6.82	22.66±10.62	27.04±19.08	7.17±1.05
A_{MKK}	14.08±8.25	9.13±6.21	8.324±4.70	14.30±10.47	19.18±15.21	4.94±0.50
R_v	85.51±2.30	86.33±9.73	77.59±17.89	79.15±3.77	75.05±1.63	95.36±1.69
R_{ps}	61.77±17.19	70.05±14.90	64.71±14.88	58.85±16.49	47.56±8.01	86.55±3.31
BCC/Al	0.10±0.05	0.13±0.07	0.31±0.43	0.09±0.06	0.13±0.04	0.90±0.44

Outliers in O-horizons were mainly beech stands whereas outlier points in TSH were also nearby spruce stands. The influence of regional specificities was still more pronounced in some cases in DH but their overall distribution reflected the topical characteristics of sampling points to the greatest extent. Therefore the point character of soil development is apparently the most typical attribute of the investigated territory.

Transformations of component vectors confirmed the synergy of common recent soil-forming factors in the potentially heterogeneous environment of soil substrates. In O-horizons pedomorphic factor 1 distinctly separated *EAl* and Al^{3+} from the other physicochemical properties but factor 3 clustered them pronouncedly in one part of the factor field (Fig. 5). In the distribution according to soil variables and according to sampling points the |***CV***|/sin*a* of O-horizons seems relatively homogeneous, distinctly modified by one pronounced factor. The more balanced synergy of several soil factors is evident in deeper horizons (Fig. 6). The variables are still assigned to one or two main clusters, corresponding to physicochemical and hydrophysical variables, but as a whole they are diverging omnidirectionally in all planes. When examining the spectrum of soil variables or sampling points, there are distinct differences in the distribution of vectors in both TSH and in DH (Fig. 7). While the relations between soil variables are of relatively homogeneous character, the projection of the |***CV***|/sin*a* of sampling points indicates the obvious heterogeneity of soils in the investigated area. However, the homogeneity of the relations of variables in TSH and DH is only apparent. The occurrences of |***CV***|/sin*a* outliers of C_{ox} and Fe_{tot} caused that the boundaries between both groups of soil horizons were detected by the robust K-W test (Table 6).

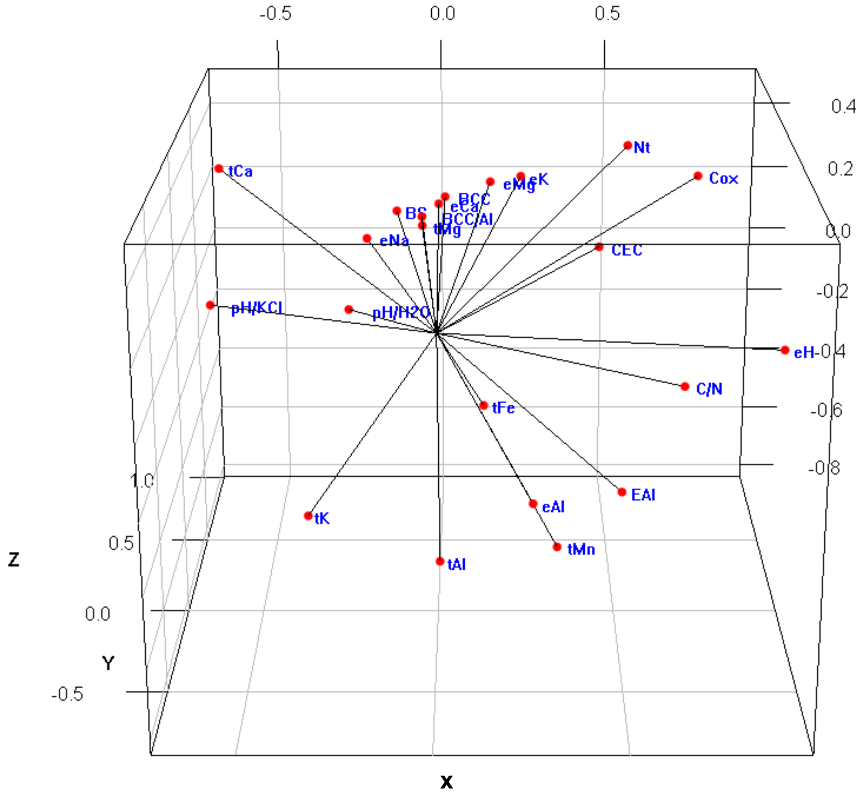

Fig. 5. 3D-projection of relations among chemical properties of organic soil horizon. X – pedomorphic factor; Y – predisposition factor; Z – hydrophysical factor (for explaination of the qualities see table 4)

Table 6. Comparisons of component vectors and soil horizon sampling points. Statistically significant differences in analyses of variance and broken normalities are detected at *P*<0.05 bold. A_1 – assymery criterion; E_1 – elevation criterion; *F* – Fischer-Snedecorov's criterion; F_{crit} – critical value of the *F*-criterions. S_A – variance among particular factor's levels; S_R – resiual variance; MS_R – average residual square

Heterogeneity factor		**Soil properties**			**Sampling points**		
Soil horizon		**OH**	**TSH – DH**		**OH**	**TSH – DH**	
Interval	Minimum	-1.98	-18.01	-86.44	-58.90	-15.95	-160.01
|*CV*|/sin*a*	Maximum	680.81	3.18	9.33	114.17	29.24	24.54
Normality	A_1	**10.07**	**10.56**	**15.44**	**6.26**	1.12	**8.71**
test	E_1	**28.17**	**29.90**	**51.65**	**15.15**	0.80	**16.84**
ANOVA	$F_{0,05}$			0.59			3.28
	F_{crit}			3.97			3.99
K-W test	S_A			7 667.05			1 196.38
	S_R			137 825.00			980.21
	S_A/MS_R			4.00			0.88
	F_e			**4.00**			**0.88**
	F_{crit}			0.00			0.00

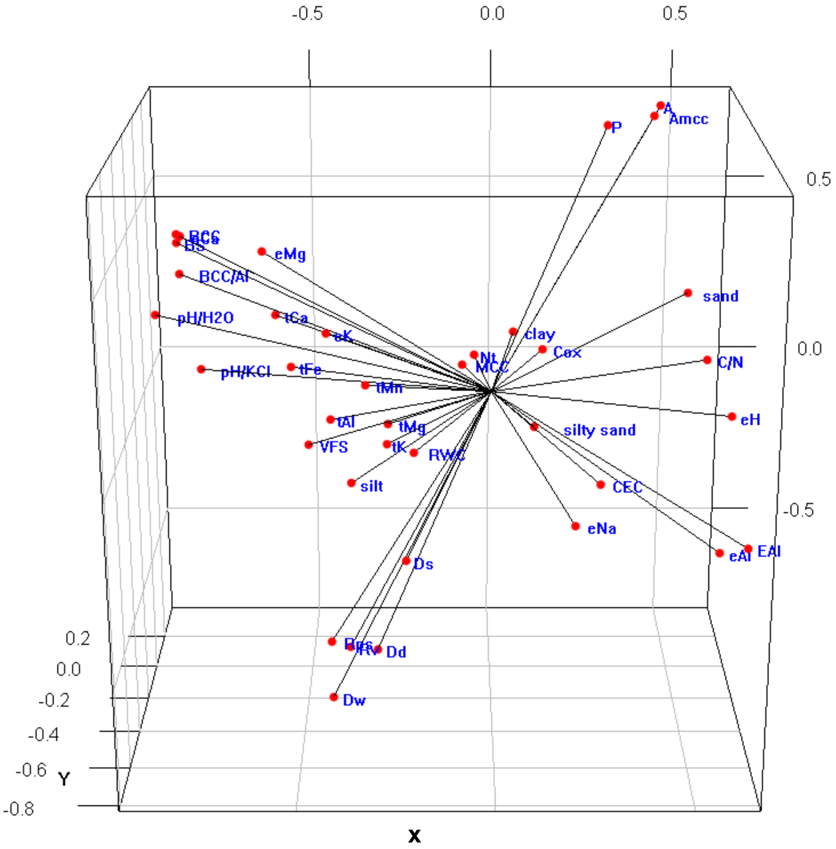

Fig. 6. 3D-projection of relations among chemical properties of organic soil horizon. X – pedomorphic factor; Y – predisposition factor; X – hydrophysical factor (for explaination of the qualities see table 4)

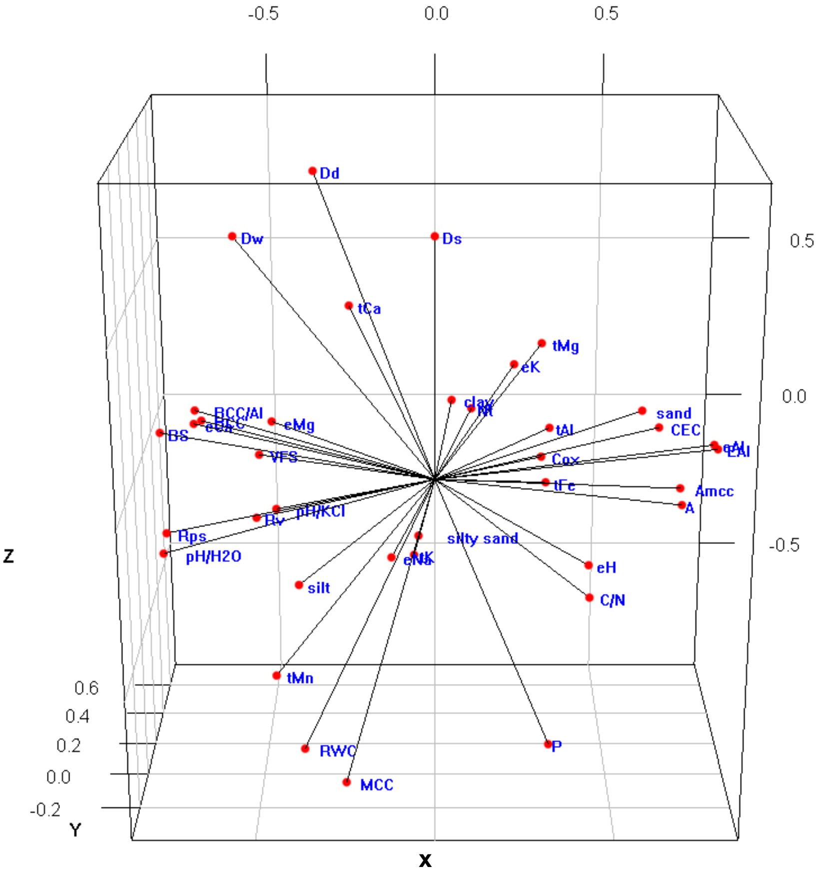

Fig. 7. 3D-projection of relations among chemical properties of organic soil horizon. X – pedomorphic factor; Y – predisposition factor; X – hydrophysical factor (for explaination of the qualities see table 5)

General Discussion

In landscape ecology the mathematical analysis of soil samples is differentiated particularly with respect to the acquisition of information on the dynamics of a system in time or determination of spatial gradients. Nonlinear models are widely applied to study the dynamics of soil systems. They are often employed to forecast landslides during earthquakes and as a result of erosion, or they are focused on the nutrient budget as influenced by fertilization and grazing. Nonlinear models of soil behaviour may be constructed as special experimental functions or they are based on the application of a general theoretical function.

Under certain assumptions differences in the dynamics of substances can be examined by strictly spatial models [2]. Biogenic elements depending on the sink in soil organic matter may have stable contents for longer time periods corresponding to the stages of natural development of the biocoenosis. Nonlinear models of ecosystem levels are constructed for regional spatial analyses. There also exist generalized models of macro-levels developed for continental or global applications. Both approaches to modelling are complicated by algorithms for a minimization of errors resulting from data aggregation to more general scales. The characteristics of litterfall or soil organic matter simulated by one- or only two-factor subsets may indicate an equilibrium state but records of its deviations at transitional sites will apparently be overvalued proportionately to data aggregation [13]. Thanks to such sensitivity the soil variables are limit components of regional models.

The unbiased expression of differences among various sites and their transitions is conditioned by the use of suitable robust multivariate analyses. The correct solution is based on the completeness of observations of variables mutually influencing one another within the system. The omission of a group of variable makes it impossible to correctly assess the significance of influences of another variable. But inconsistencies in the distribution or detection accuracy of the particular traits require to use transformations. One of the effects of data transformations is their homogenization and variance reduction. The reduction of some contingent phenomena in a multivariate field makes it possible to identify more easily the causes of a diminished influence of selected groups of variables. If a suitable transformation of the values of the particle-size composition of brackish sediments is used, secondary effects of different salinity, mineralogy and contamination sources on the variability of the metal content may be observed [17]. The application of FA in the environment of mountain forest soils allowed to identify several factors of different significance that potentially influence the health status of spruce stands although the most important differences in the properties of soils at the particular sites are conditioned by local differences in soil-forming substrates [cf. 12; 19]. Carbon and iron contents had the greatest influence on differentiation of the redundant components of correlations between soil properties.

The used linear transformation in a component field enabled to separate the factor components of soil heterogeneity in a horizontal direction. However, differences among the properties of the studied soil horizons in a vertical direction could not be determined without ambiguity. Soils on texturally variegated substrates or on lighter-textured substrates show the fractal distribution of properties [14]. On the one hand, it limits the use of linear statistical methods to find out differences among the particular soil units, on the other hand the demonstration of fractal dimensions facilitates an explanation of the character of variance in statistical comparisons [15]. In the investigated area mostly substrates of uniform texture were found out on which a mosaic of various soil types occurs. Their different properties are suggested mainly by iron contents and also by the ability of different carbon utilization. The heterogeneity of TSH properties in the investigated area is increased particularly by *CEC*. *CEC* is potentially strongly influenced by the content of soil carbon. On the contrary, it influences the content of exchange bases and the degree of *BS*. The synergy of both factor planes leads to peculiar hydrophysical conditions. Specific and volume weights, *MCC* and *RWC* remain relatively homogeneous in different soil types. But the aeration and potential saturation of soil pores along with differentiated carbon and iron values may significantly contribute to various restrictions of ecological stability, quality and desiccation of the studied soils.

CONCLUSIONS

1. The soil units described by partial variables of humification organic horizon, top-soil and diagnostic horizons behave like systems of multivariate relations.
2. In the investigated area of the Silesian Beskids the influences of three multivariate sets of factors on the overall condition of soils were determined from analyzed samples.
3. In the forest floor the set of pedomorphic factors associated with litterfall characteristics plays the most significant role. In deeper horizons its influence on total variability is reduced mainly by mineral-predisposition and hydrophysical factors.
4. Differences between top-soil horizons and diagnostic horizons were determined by robust methods only because they are little distinct. The uniformity of specific and wet bulk density, maximum capillary capacity and retention water capacity contributes to such indistinction.
5. The values of cation exchange capacity, total carbon and total iron contradict the assumption of soil horizon homogeneity. These variables influence the final heterogeneity of the occurrence of various soil types in the area concerned.

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