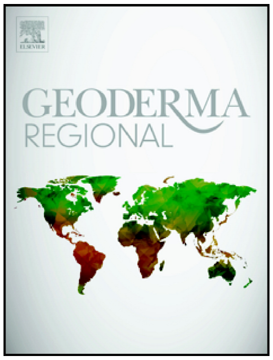

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Kolmogorov' entropy to investigate variation of forest soil properties in the Czech Republic

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Abstract: A measure of variation in values of physico-chemical properties of different soil groups is influenced by deterministic uncertainty. In this study, we assessed variation level of soil horizon properties in the most wide-spread forest soil groups on territory of the Czech Republic in the period 1953–2010. The assessment of variation was based on the selection of potentially correlating grain-size and chemical properties and a regression analysis ($p < 0.05$) between normal values (1981–2010) and Kolmogorov (K-) entropy of the forest soil quantities. Cambisols (73%), Stagnosols (10%) and Leptosols (4%) were the most frequently sampled soil groups in the database of 15,287 pits from the state pilot forest surveys during the normal period. The K-entropies of clay, N_{tot}, CaO and MgO indicated the mean contents in the soil groups more significantly than the entropies of loam, pH and Al_2O_3. The low variable clay content differentiated the series of Cambisols-Podzols (CM-PZ) from other soil groups. On the contrary, the higher stable clay content differentiated the Luvisols-Retisols-Stagnosols (LV-RT-ST) series. The low stable clay content and the higher N_{tot} and CaO contents were characteristic of Fluvisols and Gleysols. The CM-PZ series varied from LV-RT-ST by more variable contents of finer grain particles, N_{tot} and CaO. Relationships between soil properties means and K-entropies suggest different development series.

Keywords: time series analysis, deterministic uncertainty, soil development, Cambisols, Stagnosols

1 Introduction

Variation of forest soil properties is caused by environmental instability. Unsteadiness determines the unique trend of the soil development and occurrence of above-average/belowaverage soil properties values (Montagne et al. 2013). Relations among the clay or carbon contents and sorption complex differentiate in heterogeneously fertile soils (Ross et al. 2008). Continuous vegetation canopy over forest soils allows successive levelling of nutrient transformation balance and rectification of the soil development (Šebesta et al. 2011). The characteristic differences in nutrient dynamics between topsoil horizons (TSHs) and subsurface ones are segmented within setting of dynamic equilibrium in the soil development (Šamonil et al. 2011). On the one hand, humus is intensively created in TSHs, on the other hand, TSHs are more afflicted by leaching or mass runoff than subsurface horizons. Although subsurface horizons permanently have low contents of available nutrients, they are important pools of biogenic elements on account of their distinctly considerable thickness and slower properties changes course (Rumpel and Kögel-Knabner 2011). The differences in the horizon properties values among various soil groups suggest sensitivity to the environmental change (Oulehle et al. 2006).

The forest soil-forming processes are the most extensively affected by the increase in soil organic matter decomposition velocity due to global warming, the alteration in water availability owing to precipitation shifts and by more intensive acidification in consequence of acid deposition, more intensive desiccation of the landscape or cultivation of unnatural stands (Woo 2009). Global warming causes the increase in nutrient-rich soil fertility, but it leads to the limiting decrease of the nutrient content in nutrient-poor soils (Peterman and Bachelet 2012). The ecosystem acidification has been changing the ecosystem dynamics, it worsens soil nutrient availibility as well as forest health status (Fenn et al. 2006). Disrupted soils cannot effectively mitigate forest health status even though acid deposition decreases (Oulehle et al. 2012). Samec et al. (2016) suggested that the spatial relation of soil base saturation, MgO and C_{org} with atmospheric properties of the growth medium is significant for forest biomass density (cf. Purdon et al. 2004; Oulehle et al. 2010; Vacek et al. 2013). The common effect of global warming and acid deposition results in differentiation of fertility among various forest soil groups in dependence on the total nutrient content and vegetation (Peterman and Bachelet 2012). The unnatural forest stands as well as the coniferous ones are more sensitive to anthropogenic intensification of the soil acidification in comparison with the natural broad-leaved stands (Etzold et al. 2020). The forest susceptibility is more significant on the nutrient-poor soils. The natural forest stands on the nutrient-rich soils are ecologically more stable even during acid deposition (Vacek et al. 2013).

Differences between nutrient-rich and poor soils do not develop evenly. Relief and moisture regime most influence the formation of variances among soil bodies. Subsequently, the differences among the soil bodies develop arranged in series. A soil series is a system of similar earth bodies developed from the identical substrates over the same time (Indorante et al. 2014). Although the relief type limits the extent of the soil series, the composition of the soil series depends on bedrock chemistry. Disruption of vegetation cover by weather conditions alters the thickness of subsurface horizons, which divides soil properties values within bodies on the same bedrock (Molz and Faybishenko 2013). The uneven distribution of the impacts of weather disturbances alternately increases or decreases differences among diversely fertile soil series. Disruptions of soil development shorten predictability of changes in the soil properties values. While the soil properties evolving linearly are easily predictable, nonlinear development is difficult to be predicted (Detto et al. 2013). The difficulty of the comparison between linearly and nonlinearly evolving soils is reflected in different accuracy of the results of the time series analyses. Various accuracy of soil development assessment is due to the fact that the contact between soil-forming and geomorphological processes simultaneously supports convergent and divergent differentiation of the soil from the bedrock. Convergent or divergent development is indicated through: (i) podzolization; (ii) growth of the subsurface horizon thickness and (iii) soil erosion (Phillips 2000).

The aim of this study was to distinguish the forest soil groups with the linear development and the soils with potentially unstable development using the relation between the horizon properties and the measure of variation. The soil development course can be characterized as being either deterministic or chaotic. The deterministic development is predictable linearly but the chaotic one is predictable by means of quantification of irregular deviations (Kreyling et al. 2018). The variation of soil development deviations from the regular order to total disorder is indicated by the Kolmogorov' (K-) entropy (Frigg and Werndl 2010). Basically, the K-entropy is a measure of variation in the chaotic system development. Consequently, predictability is the inverse value of the K-entropy (Feng et al. 2019). K-entropy values indicate deterministic, deterministically chaotic and chaotic behaviour in time series of the observed system properties (Di et al. 2019). However, the K-entropy itself cannot distinguish between dynamic instability and self-organisation in co-evolving systems (Montagne et al. 2013). The differences among variabilities of the topsoil (TSH) and subsurface (B-) horizon properties values can suggest diverse variation of nutrient accessibility development (Detto et al. 2013). The soil series with the K-entropy indicating characteristic forest soil properties variation under temperate conditions were identified using statistical analysis.

2 Material and Methods

The distinction of the forest soils with probably linear development and the soils with unstable development was focused on the selected dominantly represented reference groups and potentially correlating soil quantities (PCQs). The soil development trend was investigated through the calculation of the normals and linear regression with the

Kolmogorov' (K-) entropy of the selected soil groups in the Czech Republic (78,866 km^2; 115–1602 m a.s.l.).

2.1 Forest soil properties

The landscape of the CR is mainly formed by the Bohemian Massif, which is covered by the Outer Western Carpathians in the east. The Bohemian Massif differs from other Central European mountain systems by means of the central plain permeated by rock cities and volcanic mountains (Neuhäuslová et al. 1998). While the Bohemian Massif covers 85% of the Czech territory, the Outer Western Carpathians occupy only 15%. The natural forest cover of the CR exceeds 98% except for alpine, rocky or peatland forestless areas. The current forest cover is 34% (Barbati et al. 2014). The soil environment in the CR consists of 23 unwaterlogged bedrock types and eight waterlogged bedrock types, ten major soil groups and 55 soil associations. Forests extend to 53 soil associations, of which the two ones occur specifically out of forest soils and the six ones occur almost strictly under the forest cover. Forest soil groups are mainly represented by Cambisols (67%), Podzols (16%), Stagnosols (7%) and Retisols (4%) (Sedláček et al. 2009).

The applied soil data originated from grain-size and chemical analyses of the pits within the state pilot surveys in the CR from the time period 1953–2010 managed by the Forest Management Institute Brandýs nad Labem (Samec et al. 2014). The fundamental matrix consisted of 15,287 pits characterizing 14 soil groups. The reference soil groups were classified according to WRB-ISSS-ISRIC (Schad et al. 2014). Soil properties were compared: grain proportion according to USDA-NRSC (1996); soil acidity by pH/H_2O and pH/KCl, cation exchange capacity (CEC) and base saturation (BS) (Vanmechelen et al. 1997); C_{org}, N_{tot} and oxides of total nutrients (Houba et al. 1989).

2.2 Statistical selection

The selection of soil groups was focused on units sampled during the normal period 1981–2010 (Durre et al. 2013). Normals are comparative average values of the 30-year period of the continual measurement. The period 1981–2010 included beginning of continuous global warming and a change in acid pollution from sulfur deposition decrease to nitrogen deposition increase (Mikšovský et al. 2014). Normal values indicate significant differences among the properties of the units being compared, as they are not biased by short-term fluctuations (Guttman 1989). The groups where sampling exceeded 0.5% from the number of all the pits were selected. Merely the nominal types were selected from naturally trophically diverse units of the soil groups of interest. The suitable nominal types (Haplic units) were compared with the percentage frequency of Skeletic, Arenic, Dystric, Albic, Stagnic and Gleyic, which constitute dominant forest soil groups in the Czech Republic (Sládková 2010).

PCQs were selected from the topsoil and subsurface (B-) horizons by dimensionality reduction using multivariate exploratory data analysis (MEDA). The selected properties of the particular horizons were algebraically unified into sets characterizing soil groups. MEDA consisted of the principal component analysis (PCA), factor analysis (FA) and cluster analysis (CLU). The soil properties were divided according to the units of determination and physical character into the subsets of grain proportion, physico-chemical and chemical properties. PCA inside the subsets of the same unit quantities indicated different dispersion of the covariations. Only one quantity with the highest influential component was selected from the quantities with similar variability (Thalib et al. 1999).

2.3 Linear modelling

Distinction among forest soils was carried out through global linear modelling (GLM). Applied GLM included normality tests on value division of the analysed soil quantities using a test of asymmetry (*A*) and elevation (*E*), correlation and regression analysis (Zar 1994). GLM approximated statistical relations among the particular soil properties and variation attributes of the selected soil groups through the linear regression analysis at $p < 0.05$. Correlations between $p > 0.05$ and $p < 0.10$ were evaluated as medium, while less significant correlations upto $p < 0.50$ were evaluated as low (Draper et al. 1966). Variation was characterised through the average absolute deviation ($\bar{\Delta}$) and the maximum K-entropy (S_0). S_0 was calculated using the equation with probability (p) (Paluš 1997):

$$S_0 = \frac{-1}{T} . \sum_{n=1}^{T} p_n . \ln p_n$$

$$p_n = \frac{e^{\frac{-(\Delta u_n)^2}{2.\sigma}}}{\sqrt{2.\pi.\sigma}}$$

$$\sigma = \overline{u^2} - (\overline{u})^2,$$

where T is the length of the time series (number of years), u_n is the annual average of the analysed quantity, Δu_n is the annual deviation of the analysed quantity values, $\overline{u}$ is the normal value of the analysed quantity and σ is mean quadratic fluctuation. The average absolute deviation was obtained as mean Δu_t among the soil properties values:

$$\bar{\Delta} = \frac{\sum \Delta u_t}{t-1}$$

$$\Delta u_t = u_t - u_{t-1}$$

The effect of $\bar{\Delta}$ on S_0 suggested the probability of the linear course at soil property variation while the comparison between the normal values and S_0 detected soil development trend by horizon properties. The critical classification value of S_0 is 0. The insignificant linear regression demonstrated the chaotic trend whilst the significant regression either nonlinear or linear trend. Nonlinear trend was derived from deterministically chaotic $S_0 \neq 0$ while (quazi-) linear trend was derived from deterministic $S_0 \rightarrow 0$ (Phillips 2006). The differences in the correlations between TSH and B-horizons indicated the rate of similarity of the soil development with the external environment or with bedrock. The similarity among the modelled forest soil group properties suggested the composition of the series from the variable soil development (Birkeland and Burke 1988).

3 Results

Nine soil groups occupy more than 99 % of the forest area in the Czech Republic. Unlike the most representative forest soil groups, Cambisols (73%) with Stagnosols (10%) and Retisols (3%) or Leptosols (nearly 4%) were sampled the most frequently. The forest soil group area proportion significantly correlated ($r^2 = 0.95$) with the sampling frequency owing to the small differences between the proportion and sampling of the marginally spread groups. The dominantly proportionate forest soils were mostly sampled more than their counterparts to the total presence. Only Podzols were sampled less distinctly and Retisols less indistinctly (Table 1). The nominal type as the representative group unit was selected for Cambisols and Retisols even though their Dystric types evinced the higher sampling frequency than the Haplic ones but at the same time they were not sampled without interruptions.

The grain-size, pH/H_2O, BS, C_{org}, Al_2O_3 a CaO formed PCQs of both compared soil horizons. The selection of the PCQs was affected by the differences in the relations of C_{org},

N_{tot} and P_2O_5 with the other soil properties at the topsoil horizons. Nevertheless, merely the correlations of C_{org} were confirmed as affecting soil variation while the correlations of N_{tot} and P_2O_5 were obtained as less influential (Table 2). The intersections between the factor and cluster analyses confirmed the correlations among the properties with the similar principal components. The clay content and pH correlated with the majority of the selected soil properties. The correlations between PCQs and base saturation, C_{org}, Al_2O_3 and CaO were more significant than in the instance of N_{tot} or MgO. On the contrary, the contents of sand or loam correlated with the other PCQs predominantly inconclusively. On the one hand, loam significantly correlated with the selected PCQs silt content and acidity, on the other hand, also with the less related N_{tot} and MgO contents (Table 3).

The significant correlations among the selected soil properties did not influence the similarities between variations in the soil horizon development. Only the development of BS at the topsoil horizons was significantly accompanied by the influence of the variation average absolute deviation on the K-entropy. Variation of the subsurface horizon properties affected the evaluated soil bodies more than the topsoil properties. The similar significance in properties variation at the grain-size fractions between TSH and B-horizons occurred sporadically between the silt contents and the contents of biogenic CaO, MgO and P_2O_5. While the contents of silt, CaO and MgO impacted the soil profile properties both in the top and subsurface horizons by low significancy, variability of the P_2O_5 content was insignificant in both compared soil horizons. By contrast, the contents of loam, clay, organic matter, Al_2O_3 and CEC influenced property variability in the entire evaluated profiles from the subsurface horizons.

Neither the selection of the mutually correlating properties nor stable variation of the soil horizon properties substantially conditioned the indication of the direction between constancy and the size of forest soil properties values. The contents of soil clay, nitrogen, CaO and MgO divided the K-entropy of the particular soil groups statistically significantly at $p < 0.01$. The coarse-grain fractions, pH, CEC, C_{org} and A_2O_3 affected the soil group K-entropy insignificantly. Contrarily, neither BS nor P_2O_5 affected the soil K-entropy (Table 4). While the clay content was selected as potentially correlating in spite of disrupted normality similarly like CaO, the soil nitrogen content was related to the forest soil group entropy even though did not correspond with the variance distribution of the other soil properties. The low correlations of CEC, C_{org} and A_2O_3 corresponded with the effect of the values in the subsurface horizons on forest soil properties variation. Only the clay content significantly divided the forest soil K-entropy at low variation between the compared horizons. On the contrary, the P_2O_5 stable content suggested low variation unconditioning the K-entropy. Different variation of base saturation in the particular soil horizons did not prove the forest soil group K-entropy division unlike the relations of clay and P_2O_5.

The dependences between the K-entropy and the sizes of the soil properties values differed in the particular forest soil group horizons. Dependence proximity was lower in the topsoil horizons compared to the subsurface ones. The lower dependence of the clay content or organic matter in the topsoil decreased the dependence at the whole soil bodies. The differences of the CaO content in the topsoil horizons conversely increased the dependence proximity of the entire evaluated bodies K-entropy (Figure 1). The diverse effect of the substance contents in the topsoil horizons on the whole soil bodies was associated with the K-entropy size, which is much higher for bound nutrients. Nevertheless, the differences of the K-entropy values among the particular forest soil groups retained the division into the series derived from the regression models (Table 5). The comparison of clay, nitrogen and CaO contents among the soil groups distinguished the occurrence of three series. The Cambisol-Podzol (CM-PZ) series was characterised by the low variable clay content < 6 % and the K-entropy > 0.24. The Luvisol-Retisol-Stagnosol (LV-RT-ST) series is conversely different by the steadily higher clay content > 4 % in topsoil horizons and > 10 % in subsurface horizons under the K-entropy < 0.22. The series of Fluvisol-Gleysol (FL-GL) was specific for the low steadily clay contents, but the higher contents of N_{tot} and CaO. Whereas the clay contents were at the series FL-GL < 4 % in the topsoil horizons and < 6 % in the subsurface horizons, the N_{tot} contents were 0.13-0.35% and the CaO contents 4.8-5.9 g/kg in TSH and 5.0-15.0 g/kg in the B-horizons under the K-entropy < 0.18.

4 Discussion

The Kolmogorov' entropy of the statistically selected soil properties distinguished the linear and deterministically chaotic development of the forest soil groups. Various forest soil deterministic uncertainty characterised diversely fertile series. The differences in deterministic uncertainty between the topsoil and subsurface horizons suggested affectability due to the external environment or self-organisation.

The relations between the K-entropy and normal values of the selected soil properties deliminated waterlogged soils (Fluvisols-Gleysols), eolian soils (Luvisols and Retisols including Stagnosols) and mixed hillwashes (Cambisols-Podzols) among the investigated forest soil groups. The more frequent stochastic K-entropy of the Cambisol-Podzol properties corresponds with the natural inclination of nutrient-poor soils towards chaotic arrangement. Fluctuations of the Cambisols-Podzols properties affect the site development the most, the LV-RT-ST impacts the site at least conversely (Montagne et al. 2013).

The various K-entropy sizes among the forest soil group series suggested different response to alteration of the chemical properties between nutrient-rich and poor sites (Ross et al. 2008). Variation in the contents of soil clay, N_{tot}, CaO and MgO demonstrated the development differences among the soil groups statistically the most. The little variable clay content associated the forest soil groups being compared into three series. Lower fluctuations of grain fractions, base saturation and the Al_2O_3, CaO and MgO contents indicated potentially linear development among Luvisols, Retisols and Stagnosols. Higher fluctuations of grain-size fractions, BS and C_{org} demonstrated deterministically chaotic development in Cambisols and Podzols. The contents of CaO and N_{tot} characterised merely the waterlogged soil series by significantly higher values and by absolute deviations. Contrarily, variable BS did not distinguish any soil entropy series although physico-chemically related pH and Al_2O_3 affected the soil K-entropy by medium significancy. The changes in BS values were very similar among all the soil groups in contrast to pH or total nutrient content variations. The fluctuations of base saturation and the clay content in the topsoil horizons were slightly more variable than in the subsurface horizons but the fluctuations of soil clay and N_{tot} were more variable than CaO. The contents of soil clay, N_{tot} and CaO were more variable in the topsoil horizons compared to the subsurface soil horizons.

The self-organised soil properties inhibited effects from the external environment within the series (Peterman and Bachelet 2012; Detto et al. 2013; Di et al. 2019). By contrast, fluctuating topsoil properties values effect as an inner-soil predispositions of the forest health status (Brunner and Sperisen 2013). The coarse-grain particles, pH and Al_2O_3 affected the soil development differences under the medium significance while C_{org} and CEC under the low significance. The soil clay content and CaO was decreased gradually whereas the N_{tot} content was increased (Samec et al. 2014). The forest soils CM-PZ in the Czech Republic have more variable contents of clay, nitrogen and CaO than LV-RT-ST. The forest soils in the Czech Republic possess temporarily stable contents of Al_2O_3, CaO and MgO while fluctuations of grain-size fractions and N_{tot} are deterministically chaotic at the various rate. The dependences between average values and variation influenced the soil predispositions at the decreasing content tendency CaO > MgO > clay > N_{tot}. The low significant correlations between the average values and variation affected the predispositions at the series loam > pH > Al_2O_3 > silt > CEC > C_{org}.

The comparison among the correlations of variations and the normal values between the topsoil and B-horizon properties suggested external effects on the earth body development in contrast to the inner-soil environment. The properties of little variable subsurface horizons affected the soil body development more than the variable topsoil properties. Low variation in the B-horizon properties is an indicator of prevailing self-organisation. The importance of dominant soil self-organisation is based on the fact that it inhibits impacts from the external environment on ecosystem (Targulian and Krasilnikov 2007). The correlations between the soil grain particles and chemical properties influenced the difference rate at the organic matter content between the topsoil and subsurface horizons alongside the various forest soil groups. Multivariate analyses demonstrated that the distribution of the values of the organic matter properties was similar to the distribution of the total chemical composition merely at the topsoil horizons. That is why the correlations among the soil properties did not relate with the similarities at the horizon development variations, but they suggested occurrence of similarly vulnerable forest soils (Purdon et al. 2004). Although the external environment, on the one hand, controls both dynamics and the forest ecosystem health status, on the other hand, impacts of its variation are concentrated predominatly on topsoil horizons (Brunner and Sperisen 2013).

The relation of the topsoil properties and forest health status is regulated by the soil organic matter composition (Fenn et al. 2006). Organic matter decomposition in acidic soils causes changes with the aluminium activity. Active aluminium damages the plant root system directly until coupling by exceedance of organic substances (Göttlein et al. 1999; Šebesta et al. 2011; Oulehle et al. 2012). Although the normals and variations of the soil organic matter contents and CaO were directly proportional to the grain-size fraction contents, the C_{org}

content was indirectly proportional to Al_2O_3. The development of BS closely relates with the fluctuations of soil clay than C_{org}. Fluctuations of Al_2O_3 afflicted not only the soil organic matter content, but also the decrease of BS was their consequence predominantly. The effect of Al_2O_3 on the decrease of BS was uneven in relation with the different influence of pH to Al^{3+} release between nutrient-rich and poor sites (Oulehle et al. 2006). When discrepancies between the higher content of C_{org} and lower BS on nutrient-poor sites indicate forest susceptibility to changes of the external environment, the contents of clay and CaO inhibit predispositions along soil group transitions.

Forests on nutrient-poor sites are more sensitive to environmental loads not only due to low nutrient contents, but also on account of their chaotic fluctuations. The distinguished series of the soil K-entropy correspond with the associations of mountain (CM-PZ), submountain (LV-RT-ST) to waterlogged (FL-GL) forest soils (Sedláček et al. 2009). In the same direction, the proportion of nutrient-poor sites decreases and the proportion of nutrient-rich sites increases (Purdon et al. 2004). Similarly, soil clay, CaO and N_{tot} K-entropy suggested that the predispositions on nutrient-poor sites were caused by greater variation of the soil properties values. On the contrary, the nutrient-rich site predispositions were limited both by higher nutrient contents and by lower chemical variation.

5 Conclusion

Both horizon properties and forest soil group proportion divide site development dynamics. The potentially correlating grain-size composition, pH, base saturation, C_{org}, Al_2O_3 and CaO specified the similarities in the distribution of the forest topsoil to the subsurface horizons. Variation of the soil clay content, CaO, MgO, N_{tot}, pH and Al_2O_3 the most significantly divided forest soil groups into the nutrient-rich, poor and waterlogged series. The disjunctive effect of the soil properties was characteristic by decreasing significance of CaO > MgO > clay > N_{tot}. The nutrient-poor series Cambisols-Podzols develop chaotically while the nutrient-rich Luvisol-Retisol-Stagnosol series is more deterministic and the waterlogged series of Fluvisols-Gleysols is relatively quasi-linear. Correlations of soil properties deterministic uncertainties and normals seem to be indicators of the forest site variation level.

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Table 1. The composition of main units and pits of the forest soil groups investigated in the Czech Republic during period 1981–2010 (%).

Soil group	Area proportion	Sampling	Main soil unit frequency						
			Skeletic	Arenic	Dystric	Haplic	Albic	Stagnic	Gleyic
Leptosols	1.18	3.99	10.58	0.17	0.34	32.08	-	1.19	-
Regosols	0.03	0.13	-	71.43	14.29	14.29	-	-	-
Fluvisols	1.14	2.56	-	2.37	-	15.98	-	23.08	18.34
Vertisols	0.02	0.05	-	-	-	-	100.00	-	-
Chernozems	0.32	0.03	-	-	-	40.00	40.00	-	-
Phaeozems	0.10	0.32	-	-	-	81.58	2.63	7.89	2.63
Luvisols	1.43	2.81	-	-	-	61.84	9.74	26.58	-
Retisols	3.59	3.29	-	7.97	47.83	43.48	-	-	-
Cambisols	66.56	72.76	4.54	2.13	36.86	28.89	3.92	4.70	0.24
Podzols	15.9	1.48	6.99	17.93	-	33.33	-	8.54	2.46
Stagnosols	7.31	9.79	-	-	40.48	33.93	6.29	-	3.66
Gleysols	0.83	0.92	-	8.66	-	36.72	-	-	3.88
Histosols	1.53	1.22	13.09	-	-	53.40	-	-	8.90
Anthrosols	0.06	0.64	8.82	8.82	-	2.94	-	14.71	-

Table 2. Dimensionality reduction among potential correlative soil quantities by the multivariate exploratory data analysis between top and diagnostic soil horizons. CEC – cation exchange capacity; BS – base saturation; PCA - principal component analysis score; FA - maximal load by factor analysis; CLU - cluster analysis (**bold** statistically significant value).

Property	Quantity	**topsoil**		**subsurface**	
		PCA	**FA∩CLU**	**PCA**	**FA∩CLU**
Grain size	sand (0.1-2 mm)	-	-	**0.99**	**-0.77**
	loam (0.05-0.10 mm)	-	-	**-0.09**	**0.84**
	silt (0.01-0.05 mm)	-	-	**-0.38**	**0.81**
	fine silt (0.01-0.002 mm)	-	-	-0.29	-
	clay (< 0.002 mm)	-	-	**-0.24**	**-0.65**
physicochemical	pH/H_2O	-	**-0.90**	-	**-0.89**
	pH/KCl	-	-0.89	-	-0.87
	CEC	-	-0.63	-	-0.61
	BS	-	**-0.65**	-	**-0.78**
chemical	C_{org}	**0.34**	**-0.75**	0.01	-
	N_{tot}	**0.01**	-	0.00	-
	Fe_2O_3	**-215.01**	0.82	79.99	-
	Al_2O_3	**-542.20**	**0.87**	**166.91**	**-0.62**
	MnO	**-0.15**	-	**-72.27**	-
	CaO	**530.91**	**-0.89**	**1959.80**	**-0.63**
	MgO	16.49	-	101.66	-
	K_2O	-10.38	-	17.55	-
	P_2O_5	**-4.24**	0.91	3.79	-

Table 3. Linear correlations among soil properties and effects of average absolute deviations on forest soil horizon K-entropy (**bold** significant at $p < 0.05$; normal lowly significant at $p < 0.50$; gray insignificant). CEC – cation exchange capacity; BS – base saturation; TSH – topsoil horizon; SSH – subsurface horizon.

Quality	loam	silt	clay	pH	CEC	BS	C_{org}	N_{tot}	Al_2O_3	CaO	MgO	P_2O_5	TSH	SSH	Body
sand	**-0.21**	**-0.37**	**-0.35**	-0.05	-0.04	-0.09	0.08	0.11	-0.26	0.00	-0.05	0.02	0.45	0.09	0.19
loam		**-0.32**	-0.06	**0.23**	-0.03	0.09	0.07	**0.24**	0.04	0.01	**-0.16**	0.04	0.34	0.06	0.09
silt			-0.02	**-0.19**	0.05	0.00	0.10	-0.08	-0.09	**-0.12**	0.08	-0.06	0.39	0.27	0.34
clay				**0.29**	**0.18**	**0.36**	**-0.28**	**-0.18**	**0.48**	**0.24**	**0.21**	-0.02	0.13	0.11	0.18
pH					**0.24**	**0.67**	**-0.16**	**0.13**	**0.18**	**0.58**	**0.12**	0.06	0.17	0.31	0.12
CEC						**0.38**	0.08	**0.13**	**0.18**	**0.16**	0.11	-0.01	0.14	0.27	0.21
BS							-0.07	0.08	**0.27**	**0.37**	**0.14**	0.00	**0.70**	0.00	0.36
C_{org}								**0.60**	**-0.21**	-0.08	**-0.15**	0.01	0.36	0.18	0.14
N_{tot}									-0.08	**0.15**	-0.09	0.03	0.24	0.33	0.32
Al_2O_3										0.10	**0.39**	0.04	0.18	0.04	0.10
CaO											**0.22**	**0.23**	0.34	0.26	0.28
MgO												**0.56**	0.32	0.37	0.27
P_2O_5													0.24	0.13	0.04

Table 4. Linear regressions between the forest soil quantities normals and Kolmogorov' entropy (**bold** significant at $p < 0.05$; normal lowly significant at $p < 0.50$; gray insignificant). *E*- elevation; *A* - asymetry; *r* - correlation coefficient; $F_{0.05}$ - Fischer-Snedecorov' criterion; *p* - probability level; *a* - slope of the function; *b* - elevation parameter.

Quantity	*E*	*A*	*r*	$F_{0.05}$	*p*	*a*	*b*
sand	-0.21	0.32	0.23	0.79	0.39	-0.0004	0.1010
loam	-0.41	-0.15	0.50	4.60	0.05	-0.0077	0.2287
silt	-0.57	0.21	0.33	1.66	0.22	-0.0014	0.1656
clay	**2.50**	**1.64**	**0.67**	**11.10**	**0.00**	**-0.0089**	**0.2441**
pH	**3.43**	**1.83**	0.45	4.04	0.06	1.2144	-0.5265
KVK	**16.98**	**4.07**	0.23	0.90	0.36	-0.0170	0.1019
BS	0.87	0.86	0.05	0.04	0.84	0.0000	0.0710
C_{org}	**5.18**	**2.45**	0.20	0.64	0.43	0.0713	0.1671
N_{tot}	**5.31**	**2.40**	**0.59**	**8.42**	**0.01**	**1.9091**	**-0.0491**
Al_2O_3	-0.02	0.38	0.43	3.69	0.07	0.0000	0.0004
CaO	**5.99**	**2.33**	**0.72**	**17.47**	**0.00**	**-0.0011**	**0.0015**
MgO	-0.53	0.50	**0.66**	**12.68**	**0.00**	**-0.0002**	**0.0020**
P_2O_5	-1.33	0.33	0.14	0.32	0.58	0.0017	0.0037

Table 5. Kolmogorov' entropy of the potentially correlating quantity time-series in the investigated forest soil groups during the normal period 1981–2010.

Quantity	Horizon	Histosols	Fluvisols	Gleysols	Leptosols	Cambisols	Podzols	Stagnosols	Retisols	Luvisols
sand	topsoil	-	0.067	0.073	0.081	0.123	0.078	0.098	0.085	0.095
	subsurface	-	0.069	0.076	0.075	0.125	0.079	0.095	0.077	0.112
loam	topsoil	-	0.138	0.144	0.140	0.183	0.147	0.167	0.126	0.129
	subsurface	-	0.115	0.150	0.153	0.212	0.160	0.197	0.128	0.139
silt	topsoil	-	0.105	0.101	0.116	0.177	0.133	0.115	0.108	0.092
	subsurface	-	0.106	0.118	0.124	0.179	0.127	0.118	0.120	0.094
clay	topsoil	-	0.154	0.169	0.167	0.274	0.283	0.206	0.215	0.185
	subsurface	-	0.173	0.118	0.104	0.275	0.247	0.159	0.125	0.128
pH	topsoil	0.281	0.331	0.307	0.325	0.075	-0.099	0.009	0.244	0.328
	subsurface	0.300	0.330	0.320	0.337	-0.032	-0.287	0.219	0.147	0.334
BS	topsoil	0.094	0.065	0.048	0.078	0.069	0.088	0.079	0.062	0.054
	subsurface	0.065	0.056	0.044	0.099	0.086	0.089	0.062	0.056	0.051
C_{org}	topsoil	0.144	0.310	0.156	0.292	0.311	0.255	0.307	0.242	0.254
	subsurface	0.117	0.343	0.325	0.006	-0.057	0.330	0.287	-0.347	0.324
N_{tot}	topsoil	-0.038	-0.888	0.039	-1.295	-0.570	-1.734	-3.485	-2.017	-0.941
	subsurface	-0.051	-0.975	-0.076	-1.847	-0.661	-2.451	-4.892	-2.942	-1.376
Al_2O_3	topsoil	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	subsurface	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CaO	topsoil	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.001	0.001
	subsurface	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.002	0.000

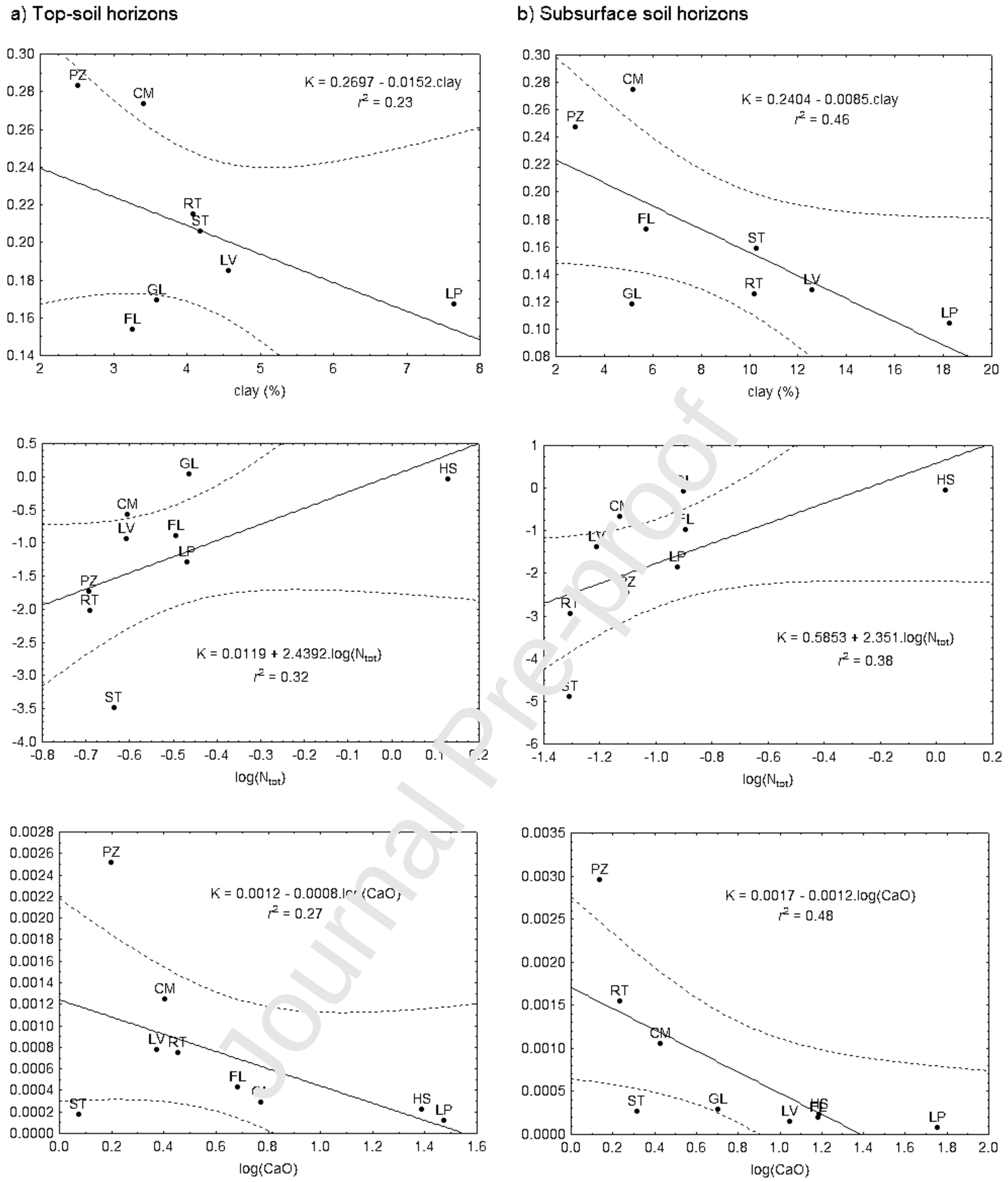

Figure 1. Relations between Kolmogorov' entropy and contents of clay, nitrogen and calcium in the topsoil and subsurface horizons of the investigated forest soil groups.

- Soil properties normals are correlated to Kolmogorov' (K-) entropy.
- K-entropy differentiates nutrient-rich, poor and waterlogged soil series.
- Nutrient-rich forest soil N_{tot}, CaO and clay are less variable than in poor soils.
- Forest soil K-entropy seems to be an environmental indicator.