Fluctuations in the Properties of Forest Soils in the Central European Highlands (Czech Republic)

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Abstract

Samec P., Kučera A., Tuček P. (2014): **Fluctuations in the properties of forest soils in the Central European highlands (Czech Republic)**. Soil & Water Res., **9**: 201–213.

Fluctuations in forest soil properties were described using a time series analysis of the clay content, the chemical (CaO, MgO, C_{org}, and N_{tot}) and physicochemical (pH and base saturation (BS)) soil parameters from 1953 to 2008. The analysis involved the dominant acidic, nutrient-rich, and waterlogged forest ecosystems on the territory of the Bohemian Massif and the Outer Western Carpathians (Czech Republic). Trends in the development of the time series of soil properties were optimized by Gauss-Newton's transformation of the exponential combination of the cyclometric function and Euler's number. Identical functions of regression equations on the fluctuations of nutrients, pH, BS, and C_{org} indicated parallel trends of soil development in different forest ecosystems. Equations representing identical, predictable patterns in C_{org} fluctuation indicated the stability of the trend. Differences in temporal patterns of nutrients, pH, and BS in different forest ecosystems indicated the susceptibility of developmental trends to external factors. Different regression equations of fluctuations of soil clay and N_{tot} indicated the occurrence of permanent differences during the soil development. During the period of 1953–2008, soil pH, BS, and CaO concentration decreased but the content of C_{org} and N_{tot} increased. Regression functions indicate that pH and BS of forest soils in the Czech Republic have temporarily increased and the content of C_{org} and N_{tot} have decreased during the period 2009–2014. Continuous increase in BS is only sustainable if concurrent with an increase in C_{org}.

Keywords: acidification; cyclometric functions; forest ecosystem; soil chemistry; time-series

Soil properties are naturally subject to many fluctuations that indicate the development of ecological soil conditions. A time series analysis is used to model the fluctuations of soil properties (Heuvelink & Webster 2001). Seasonal soil property fluctuations are governed by the cycles of the external physical environment. Multi-year fluctuations in soil properties depend on mutual relations among external factors and on internal factors of the soil development. Forest soils develop more or less naturally and can thus form a matrix for estimates of the deviations of succession in other ecosystems (Borůvka *et al.* 2007). Models of forest soils ecology are usually defined using a set of chemical balance equations and applied to catchments (Lin 2006). However, these models can only provide probable soil development predictions provided that there exists a constant system of response to internal or external stimuli (Cosby *et al.* 2001). The success rate of soil development prediction depends on the closeness of modelled and empirical data approximation, modelled system constancy, and the methodology of data acquisition and utilization within the model (Cox 1981). On the one hand, the models of soil development in small forest catchments form the basic matrix to observe the response of forest ecosystems to acid deposition and allow validation of generalized acidification models, while on the other hand they mainly suit the meso-level environmental models only (Christoph & Rafig 2012). The macro-level of environmental modelling is directly connected to the observation of soil development in properly generalized ecological landscape units (Schröter *et al*. 2005). Ecological landscape differentiation is relevant at the macro-level of environmental modelling, which allows for broader observation that depends on the climate, vegetation, water regime, and pollution.

The spatial-temporal variation in soil properties is related to nutrient and water cycles in the ecosystem. The most important cycles in the balance of mass in forests are the carbon, nitrogen, and phosphorus cycles. Acidification is usually indicated by means of changes in pH, balance of basic cations (Ca^{2+}, Mg^{2+}, K^{+}), and activity of Al^{3+} (Puhe & Ulrich 2001). The soil nutrients dynamics depends on seasonal temperature cycles and the hydric soil regime. Influences of temperatures and hydric regime are manifested in organic matter deposition on the soil surface with leaf-fall, seasonal fluctuation in root-exuded substrates, and temporal patterns of anaerobic conditions. Soil in the subsurface is exposed to waterlogging much more frequently and for a longer time period than in the root-zone depth, resulting in prominent periods of anaerobic conditions (Stoeckel *et al*. 2001).

The considerable fluctuations in the nitrogen cycle cause the most significant changes in soil development (Galloway *et al*. 2008). Progressive nitrogen saturation leads to further soil nitrogen leaching, eutrophication of water, ecosystem re-acidification, and a reduction in the soil carbon pool (Oulehle *et al*. 2012). While sulphate concentrations decreased simultaneously with the decrease in sulphur deposition, the decrease in nitrate leaching was non-linear in relation to the change in nitrogen deposition. In an acidified environment, the soil biological activity decreases, the humus substances production decreases, and the nitrate production increases (Laverman *et al*. 2000). Fluctuations in soil carbon cycles mainly occur due to changes in the balance between above-ground and underground resources (Wang *et al*. 2012). Nevertheless, to specifically estimate soil property changes requires the formulation of models that assume the influence and synergy of both acid deposition and climatic changes (Dieleman *et al*. 2010).

In this study, we focused on a soil condition development description within forest ecosystem units (FEUs) using a time series analysis. The time series analysis fundamentally focused upon the prediction of subsequent soil condition development. The problems regarding the prediction of fluctuations of soil properties relate to issues involving the determination of the length of the period during which soil development is observed, spatial extent determination for the proper application of the prediction function, selection of the soil parameters subject to fluctuations, and the trend analysis used (Christoph & Rafig 2012).

The time series analysis was based on testing and comparing hypotheses relating to periodic functions. Short-term soil development observations were extrapolated using approximated periodic functions of the medium-term soil property behaviour. The nature of the relationship among some of the soil parameters is that of an exponential function (Lee *et al*. 2003) but in longer time periods they are subject to cyclic oscillations (Heuvelink & Webster 2001). Degradation of forest soils was most influenced by erosion after deforestation, acid deposits, and repeated cultivation of monocultures (Evans *et al.* 2001; Klimo *et al*. 2006; Oulehle *et al*. 2010). During the post-war period, the territory of the Czech Republic was strongly affected by acid deposits (Akgöz *et al*. 1995). This pollution calamity peaked in 1979–1994, and thermal power stations were completely desulphurized in 1998 (Klimo *et al*. 2006). The time series of soil parameters witnessed the period of post-war reconstruction (1953–1978), the culminating pollution calamity (1979–1994), the subsequent stabilization of soil conditions (1995–2000), and the manifestations of residual acidification (Oulehle *et al*. 2010). A combination of goniometric and exponential functions enabled the testing of hypotheses relating to medium-term stable, regularly or irregularly variable and constantly rising/declining fluctuation trends of forest soil properties. The discussion was focused on the causes of the investigated fluctuations in soil properties and predictions of the obtained trends in the forest soil development.

MATERIAL AND METHODS

Soil data. The basic data matrix was compiled using the results of state pilot surveys of forest soils and state forest ecosystem classification (FEC) on the territory of the Czech Republic (CR), Europe. The CR is situated in the region of the Bohemian Massif and the Outer Western Carpathians. The Bohemian Massif is the core area of the Central European Hercynian highlands. The Outer Western Carpathians are a part of the Carpathian Flysh belt

(McCann 2008). Both parts of the CR are significant areas for the general characteristics of Central European natural conditions (Puhe & Ulrich 2001). The most frequent FEUs in the CR are nutrient-rich highland sites (NHS) (42%), acidic sites (AS) (22%), and waterlogged highland sites (WHS) (13%), mapped according to indicative plant communities. The NHSs are mainly composed of the *Dentario enneaphylli-Fagetum* association and ravine forests of the alliance *Acerenion*. The ASs include the forest societies *Genisto germanicae-Quercion*, *Melampyro nemorosi-Carpinetum* up to *Luzulo-Fagion*. WHSs include primarily the alliances *Alnion glutinosae* and *Betulion pubescentis* (Ellenberg 1996). These groups of ecosystems cover 77% of forest soils in the CR and only data from these sites were arranged into a continuous time series (Samec *et al.* 2012). A more detailed examination of the time series was prevented either by missing data, missing soil type classification, or only a short-term section record.

The basic matrix included the primary results from the determination of soil properties from forest ecosystem surveys (FES) of forest sites from 1953–2008 (6237 pits), from dendrometrical measurement plots (DMP) from 1980–2007 (979 pits), from national forest inventory (NFI) from 2001–2004 (7189 pits), and from forest nutrition surveys (FNS) from 1999–2007 (2974 pits) (Jankovská & Štěrba 2007; Samec *et al.* 2012; Vacek *et al.* 2013). The data were usually acquired from a single sampling at a given site. A typical feature of the matrix is a strong irregularity in the spatial and temporal composition of the forest types. Soil type classification is only applied in FESs on a long-term basis. The soil type has not been determined in DMP pits since 1996 and in FNS. The soil types in NFI pits were only determined semiquantitatively according to the assumed relation of soil units and forest types in the maps of regional forest development plans because the sampling method did not require the genetic soil horizons separation (Jankovská & Štěrba 2007). The common FEUs were aggregated management populations of forest types (AMP) in the applied results of the field surveys. They were derived from combinations of subsequent vegetation tiers and ecological series from the site classification database of the analyzed soil pits. The reason for using the AMPs was to achieve a density of approximately 1 pit per km^2 of forest while maintaining the principles of FEC (Viewegh *et al.* 2003). The NHSs in the basic matrix included 8368 pits (36%), the ASs 5699 pits (25%) and the WHSs 2958 pits (13%). The DMP and FNS surveys were situated in mature stands, the FES surveys were situated in representative stands of individual working plan areas, and NFI was focused on random sampling. Some planned changes in the methods of soil parameters laboratory analyses occurred during the studied period. The amount of sampled pits fluctuated year-on-year in individual regions of the CR, and the amount of soil investigations associated with different sampling procedures gradually increased. The forest soil surveys methods were changed in 1971 and in connection with legislative changes in 1995–1998. Methodical changes in soil parameter laboratory analyses in FES's occurred in 1983 and 2001, in DMP's in 1996. Top-soil horizons (TSH) data and sub-surface diagnostic horizons (DH) data were selected from source matrices. TSH were selected from organo-mineral (A), including eluvial (Ep), horizons without surface humus data (L–F–H).

The soil parameters selection depended on the methodology of soil acidification trends estimation (Vanmechelen *et al.* 1997; Klimo *et al.* 2006; Oulehle *et al.* 2012). Soil parameters were grouped as trophically indicative physicochemical properties (Ellenberg 1996) and substrate characteristics of clay fraction (CF < 2 μm) and total nutrients contents (Hunt 1972). The basic physicochemical parameters, pH_{H_2O}, pH/KCl, base saturation (BS), organic carbon (C_{org}), and total nitrogen (N_{tot}) were chosen as trophically indicative soil parameters. The values of these parameters in soils naturally fluctuate because they are directly related to biological activity, vegetation metabolism, and material cycles (Puhe & Ulrich 2001). The CF content and total CaO and MgO contents were observed as comparative substrate characteristics. CF and chemical composition of the soil mantle are the attributes of the soil-forming substrate and their content in soils does not fluctuate within short periods. Their oscillations naturally indicate the soil development. The contents of CF or nutrients fluctuating on a short-term basis were used to find sampling inaccuracies and to identify unrepresentative pits for the observation of soil development trends.

Soil pH was determined by a combination glass electrode (soil:H_2O or 1M KCl = 1:2.5). BS was calculated using the ratio of exchange bases and cation exchange capacity (White 1987). The cation exchange capacity was determined by the extractions in NH_4OAc until 2000 (Blakemore & Metson 1960) and, later, by the extractions in $BaCl_2$ (Vanmechelen *et al.* 1997). C_{org} was determined using the oxidation-titration method (Walkey & Black 1934) until 1982. Between 1983–2000 it was determined according to Nelson and Sommers (1982), and later instrumentally pursuant to ISO 10694. N_{tot} was determined by kjeldahlization (Houba *et al.* 1989) until 2000, and, later, by the Dumas method (Buckee 1994). The content of CF was determined by the pipette method until 1983, and, later, sedimentographically (Hunt 1972). Total contents of the nutrients were determined by *aqua regia* extraction (Houba *et al.* 1993). The NFI data do not contain any substrate properties. FNS and DMP data do not contain CF determination after 1996.

Statistical analysis. Data from 1953–2008 were used to determine the models of soil parameter fluctuations and their predictions. The formation of models involved exploratory data analysis (EDA), predictive function optimization of soil parameters and its comparison with the input data. The EDA was focused on determining the linear correlations at $P < 0.05$. For selected time series of soil parameters, functions expressing short-term fluctuations trends were approximated. We tested the approximations of relationships between the value of the investigated soil parameter in year t (x_t) and the remote value by period λ (x_{t+} λ) using basic cyclometric functions. Cyclometric functions record the repeatability of events. The occurrences of irregular deviations were reduced by the implementation of Euler's number. By mutual combinations of basic cyclometric functions and the basis of natural logarithms, we designed four theoretical trend functions. The proposed four equations were parameterized for individual soil properties in selected soil horizons of individual FEUs. The approximation with the highest average value of correlation index (I_{xy}) was selected from four alternatives:

$$x_{t+\lambda} = a \times \sin \frac{x_t}{b} + c \qquad (1)$$

$$x_{t+\lambda} = a \times \cos \frac{x_t}{b} + c \qquad (2)$$

$$x_{t+\lambda} = a \times e^{\sin \frac{b}{x_t}} \qquad (3)$$

$$x_{t+\lambda} = a \times e^{\cos \frac{b}{x_t}} \qquad (4)$$

where:

a – slope of the function

b – elevation parameter

c – constant

The parameters of functions *a*, *b*, and *c* were optimized by Gauss-Newton transformation (Walter & Pronzato 1997). The period length was at least one year; the maximum was 10 years. Using the absolutely highest I_{xy}, the closest approximation of the relation $x_{t+\lambda}$ and x_t was selected (Kenney & Keeping 1947), which indicated the predicted period of the development of parameter x in time. The prediction was obtained by calculation of x_{t+} λ using x_t from the empirically normal period 1979–2008. The normal is the average reference level of 30 years of undisturbed measuring (Guttman 1989). The normal and predicted values were statistically compared. Eqs (1) and (2) formed a pair of goniometric regression equations. Eqs (3) and (4) formed a pair of exponential regression equations. Prediction periods (λ_τ) were divided into short-term (≤ 2 years) and potentially medium-term (> 2 years) (Cox 1981). By combining the pairs of regression equations and λ_τ four approximation groups (AG) were searched for: goniometric short-term prediction (approximation 1), exponential short-term prediction (approximation 2), goniometric medium-term prediction (approximation 3), and exponential medium-term prediction (approximation 4). The changeability of predicted values with respect to empirical normal values of selected parameters was tested by analysis of variance (ANOVA) at $P < 0.05$ to assess the differences between the estimated parameter values in soil horizons, while F-test and t-test were used to assess the differences between empirical normals and predictions.

RESULTS

Linear correlations. Selected soil properties of model FEUs were mutually correlated to a different extent. Statistically significant correlations were mostly detected in CaO and C_{org} with respect to both physicochemical and chemical parameters. C_{org} usually correlates with other parameters negatively. Exceptions that prove the rule are the positive correlations of C_{org} and N_{tot}. In the character of correlation dependence, WHSs differ from the remaining model sets. No significant correlations of BS and pH were detected in WHSs. Relatively, the best correlations in these soils occurred in C_{org} and N_{tot}. Significant correlations occurred between CaO and pH and BS in acid and nutrient sites. C_{org} was in negative correlation with pH, BS, CaO, and MgO in acid and nutrient-rich sites. CF was detected in statistically significant correlations with BS, CaO, and N_{tot} in soils at nutrient-rich sites only. In soils at WHSs, correlations of pH, CaO, and N_{tot} with CF were marginally significant but they were solely negative. The increase of the total content of soil nutrients usually corresponded to the increase of the values of physicochemical parameters. On the contrary, the increase of C_{org} was usually accompanied by a decrease in the values of physicochemical parameters. Inclinations to an increase in the values of physicochemical parameters were the highest at NHSs on average. Inclinations to a decrease in the values of physicochemical parameters were the highest at acid sites on average (Table 1).

Time series analysis. In the drawn-up time series of soil properties three basic variability trends were detected: value decrease, value increase, and occurrence of relatively stable values. Tendencies to stable values were only detected sporadically depending on the length of the studied period; they only occurred in CF in DHs in all compared FEUs. The $\overline{\Delta} \approx 0$ temporarily (1979–2008 and 1988–1999) occurred in slightly changeable C_{org} and N_{tot} and influenced their generally lower $\overline{\Delta}$. Most values of the studied parameters were time-variable. Their downward or upward tendency was frequently accompanied by relatively regular fluctuations of higher and lower deviations. None of the detected deviations occurred during the years of declared changes in the methodology of soil investigations; nevertheless, different sampling quantities manifested themselves in the occurrence of random deviations by outliers. Changes in the laboratory methods had no impact on the soil properties deviations course, while different numbers of processed samples and their varied representativeness influenced the fluctuations of soil clay, BS, and total nutrients content before 1971. A downward tendency was most significant in pH, BS, and CaO, while also declining slightly in clay in top-soils (Figure 1), but also in N_{tot} in diagnostic horizons. Significant decreases in pH values were detected after 1965. During 1965–1972 and 1982–1992, local minima occurred in most BS. Since 2001, a slight increase in the values of soil pH and BS in top-soils has occurred. However, no such increase occurred

Table 1. Correlations (bold at $P < 0.05$) between time-series of soil properties of selected forest ecosystem units

AMP	Quality	Top-soil horizons							Diagnostic horizons						
		pH/H_2O	pH/KCl	BS	CaO	MgO	N_{tot}	C_{org}	pH/H_2O	pH/KCl	BS	CaO	MgO	N_{tot}	C_{org}
AS	CF	–0.07	–0.06	0.00	0.08	–0.09	–0.02	–0.12	0.19	0.14	**0.32**	0.19	0.12	–0.20	–0.24
	pH/H_2O		**0.94**	0.61	**0.69**	0.16	0.19	**–0.55**		**0.96**	**0.55**	**0.65**	0.09	0.26	**–0.41**
	pH/KCl			**0.62**	**0.72**	0.17	0.24	**–0.57**			**0.58**	**0.68**	0.21	**0.30**	**–0.45**
	BS				**0.34**	0.01	0.13	**–0.54**				**0.36**	0.11	0.11	**–0.45**
	CaO					**0.31**	0.19	**–0.50**					0.10	0.18	**–0.32**
	MgO						0.11	**–0.34**						–0.12	**–0.36**
	N_{tot}							–0.04							0.19
NHS	CF	**0.32**	0.26	**0.56**	**0.32**	–0.12	**0.42**	**–0.28**	0.16	0.10	**0.54**	**0.37**	–0.09	**0.33**	–0.13
	pH/H_2O		**0.89**	**0.71**	**0.69**	–0.05	0.24	**–0.32**		**0.94**	**0.60**	**0.54**	–0.09	0.04	**–0.39**
	pH/KCl			**0.62**	**0.65**	0.06	0.17	**–0.31**			**0.48**	**0.48**	–0.11	0.00	**–0.39**
	BS				**0.62**	–0.09	**0.34**	–0.22				**0.46**	–0.07	0.00	**–0.35**
	CaO					0.25	0.17	**–0.30**					0.26	0.10	**–0.36**
	MgO						–0.24	**–0.40**						**–0.36**	**–0.55**
	N_{tot}							0.32							**0.43**
WHS	CF	0.13	0.18	0.15	–0.02	0.01	–0.22	–0.18	**–0.30**	–0.21	–0.24	**–0.32**	0.01	**–0.43**	–0.18
	pH/H_2O		**0.96**	–0.13	**0.67**	–0.23	0.01	**–0.33**		**0.93**	0.15	**0.66**	0.00	–0.03	**–0.28**
	pH/KCl			–0.16	**0.66**	–0.22	–0.08	**–0.36**			0.05	**0.62**	–0.11	–0.05	**–0.29**
	BS				–0.02	0.04	0.02	0.14				**0.30**	**0.39**	**–0.34**	–0.12
	CaO					0.12	0.21	**–0.38**					**0.36**	0.05	**–0.38**
	MgO						–0.21	–0.23						**–0.32**	**–0.36**
	N_{tot}							0.52							0.51

AS – acidic sites; NHS – nutrient-rich highland sites; WHS – waterlogged highland sites; CF – clay fraction; BS – base saturation; AMP – aggregated management populations in diagnostic horizons (Figure 2). The WHS soils are an exception, indicating the trend of stable values up to a slight increase in BS. Upward tendency was detected in the values of MgO and C_{org}. Their prediction, however, is subject to discussion due to the occurrence of various value deviations.

The detected fluctuations in the soil properties were usually approximated by means of regression equations in a statistically significant way. Eq. (3), based on exponential function with sine exponent, most frequently corresponded to the empirical data. Eq. (2), on the contrary, did not show any statistically significant similarities to empirical data. Changes in the content of CF in top-soil horizons were approximated by Eq. (4), while in diagnostic soil horizons, approximation was best demonstrated by Eq. (3). The total nutrients contents were always approximated by Eq. (4). All substrate variables had a moderate development trend that was only affected by the occurrence of unusual values during short episodes especially in the early periods of field surveys until 1965. The pH values were always approximated by Eq. (1), BS by Eq. (3), and N_{tot} and C_{org} by Eqs. (1) and (3) (Table 2).

NHS soil properties achieved the best approximations with theoretical functions. Unlike ASs and WHSs, they were less affected by outliers. Only the sites with significant representation and sufficient

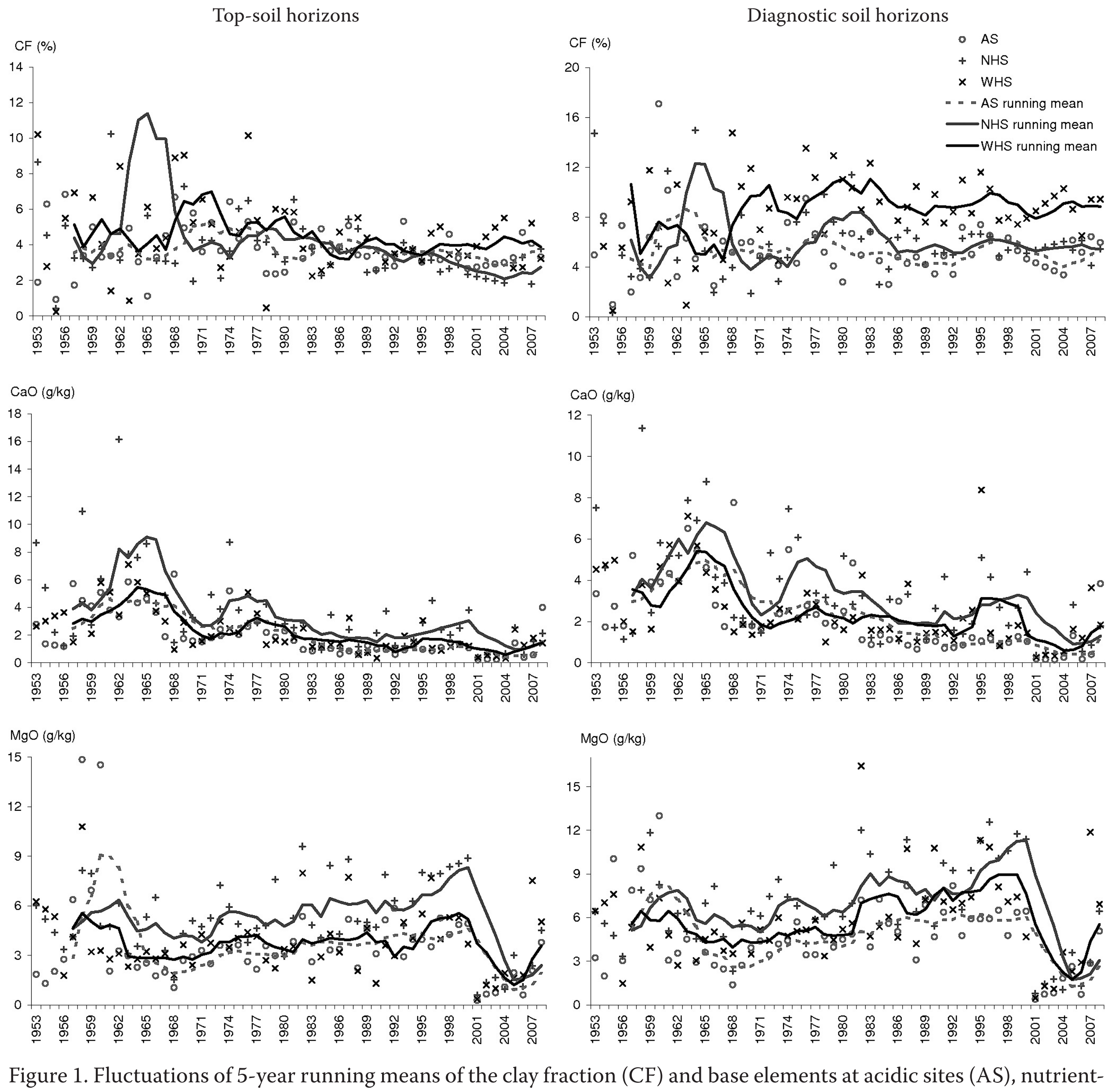

Figure 1. Fluctuations of 5-year running means of the clay fraction (CF) and base elements at acidic sites (AS), nutrient-rich highland sites (NHS), and waterlogged highland sites (WHS)

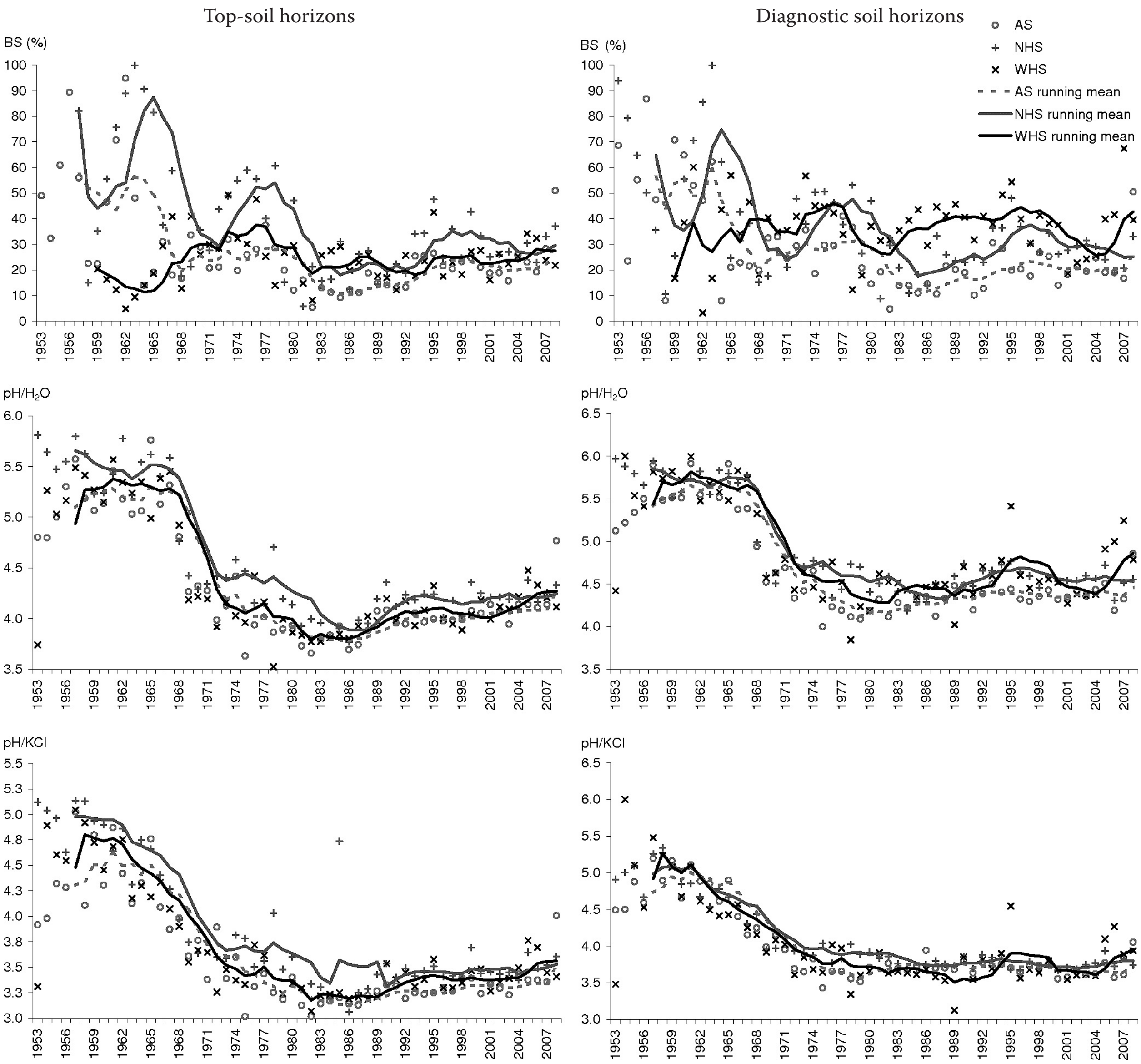

Figure 2. Fluctuations of 5-year running means of the soil base saturation (BS) and soil pH at acidic sites (AS), nutrient-rich highland sites (NHS), and waterlogged highland sites (WHS)

input data provided a robust basis for the analysis of trends in the changes of soil properties. The average clay content in TSHs of forest soils at NHSs was 3.2%, while in DHs it was 5.8%. The most significant decrease in pH/KCl in these soils (from 4.8 to 3.6 in TSHs, and from 4.7 to 3.9 in DHs) occurred between 1962–1973. Progressive changes in BS, CaO, and N_{tot} corresponded to the decreasing trend. The BS slightly increased from 18.6 to 35.9% in top-soil horizons, and from 22.9 to 36.9% in diagnostic horizons during 1992–1997. During 1998–2008, the soil BS decreased to 30 and 32% respectively, again. During the same period, an increase in the values of C_{org} occurred in both investigated soil horizons.

Statistical prediction of the soil properties development. The success rate of the prediction of the content of soil clay, pH, C_{org}, and N_{tot} in top-soils and diagnostic soil horizons varied. However, the prediction of C_{org} inclined to a bigger residual dispersion of estimated values as well. The soil organic carbon content in DHs at widely represented NHSs was stable on a medium-term basis, while at WHSs it was very unstable on a short-term basis. Its content at acid and waterlogged sites increased significantly after 1996 (Figure 3). No clear inclination to stable values to subsoil occurred among the parameters in TSHs and DHs, and so there were no distinguishable changes in the application of external or internal succession

Table 2. Parameters and attributes of the soil prediction functions and calculated normal and predicted values of soil properties at the leading forest ecosystem units (FEU) in the Czech Republic

Horizon	Quality	FEU	Equation	λ	AG	*a*	*b*	*c*	Δ^-	I_{xy}	Normal	Prediction	Δ^2
Top-soil	CF (%)	AS	4	5	4	2.70	4.47		0.03	0.98	3.53	3.78	0.06
		NHS	4	6	4	5.35	7.62		–0.01	0.90	3.22	3.63	0.17
		WHS	4	3	4	3.80	5.98		0.09	0.96	4.03	4.45	0.18
	pH/H_2O	AS	1	3	3	10.11	3.84	–4.67	0.03	0.90	3.99	3.99	0.00
		NHS	1	3	3	10.71	3.88	–5.15	–0.01	0.86	4.13	4.26	0.02
		WHS	1	3	3	8.54	4.34	–2.73	0.02	0.87	4.03	4.05	0.00
	pH/KCl	AS	1	4	3	–1.28	1.21	3.86	0.03	0.89	3.29	3.33	0.00
		NHS	1	5	3	7.64	3.80	–2.46	–0.01	0.91	3.47	3.64	0.03
		WHS	1	5	3	–1.44	1.26	4.09	0.02	0.85	3.36	3.42	0.00
	BS (%)	AS	3	5	4	54.01	–16.69		0.75	0.75	19.08	26.47	54.55
		NHS	3	5	4	66.61	–18.18		–0.79	0.77	26.48	38.62	147.38
		WHS	3	5	4	48.71	–17.56		0.26	0.87	23.38	25.23	3.42
	CaO (g/kg)	AS	4	8	4	1.89	2.65		0.06	0.95	1.07	1.60	2.80
		NHS	4	4	4	2.79	3.96		–0.07	0.88	1.96	3.18	14.73
		WHS	4	7	4	1.89	2.75		0.00	0.96	1.34	1.85	2.53
	MgO (g/kg)	AS	4	4	4	2.63	3.87		0.01	0.76	3.32	4.19	7.68
		NHS	4	7	4	3.63	5.80		–0.01	0.97	5.37	6.20	6.92
		WHS	4	6	4	3.90	6.04		0.08	0.96	3.74	4.28	2.88
	N_{tot} (%)	AS	3	5	4	0.17	0.68		–0.01	0.74	0.27	0.22	0.00
		NHS	3	5	4	0.18	0.80		0.00	0.78	0.34	0.31	0.00
		WHS	1	5	3	0.17	0.66	0.20	0.00	0.30	0.26	0.27	0.00
	C_{org} (%)	AS	3	5	4	5.55	–1.59		–0.04	0.64	4.61	3.70	0.82
		NHS	3	5	4	8.77	–3.40		0.05	0.85	5.31	4.45	0.73
		WHS	3	4	4	8.30	–2.81		0.00	0.69	4.79	4.48	0.10
Diagnostic	CF (%)	AS	3	4	4	10.48	–3.74		0.03	0.64	4.94	5.34	0.17
		NHS	3	4	4	11.78	–3.81		–0.15	0.54	5.83	6.41	0.34
		WHS	3	3	4	4.39	6.89		0.09	0.74	9.15	8.81	0.11
	pH/H_2O	AS	1	3	3	9.35	4.69	–3.08	0.02	0.93	4.35	4.36	0.00
		NHS	1	3	3	0.86	0.83	5.21	–0.01	0.84	4.53	4.63	0.01
		WHS	1	2	1	0.95	0.86	5.32	0.03	0.86	4.56	4.55	0.00
	pH/KCl	AS	1	3	3	10.43	3.47	–5.38	0.02	0.93	3.71	3.75	0.00
		NHS	1	5	3	15.25	3.19	–10.28	–0.01	0.77	3.77	3.91	0.02
		WHS	1	4	3	11.89	11.22	–0.09	0.02	0.92	3.73	3.77	0.00
	BS (%)	AS	3	4	4	47.94	–13.71		0.46	0.49	19.25	26.14	47.57
		NHS	3	2	2	63.87	–20.79		–0.67	0.52	27.30	34.25	48.27
		WHS	3	4	4	58.53	–15.95		0.91	0.81	37.28	38.43	1.34
	CaO (g/kg)	AS	4	5	4	1.34	1.41		0.06	0.70	1.21	2.13	8.48
		NHS	4	3	4	2.15	3.10		–0.05	0.59	2.20	3.11	8.29
		WHS	4	2	2	2.42	5.28		0.03	0.83	1.86	1.93	0.05
	MgO (g/kg)	AS	4	4	4	2.39	2.85		0.01	0.76	4.71	5.50	6.19
		NHS	4	2	2	3.43	4.59		0.01	0.56	7.25	7.78	2.82
		WHS	4	4	4	2.25	3.46		0.12	0.54	6.44	5.14	16.90
	N_{tot} (%)	AS	3	5	4	0.07	0.26		0.00	0.75	0.10	0.07	0.00
		NHS	1	5	3	1.15	3.49	0.09	0.00	0.41	0.14	0.12	0.00
		WHS	1	6	3	0.12	0.19	0.05	0.00	0.36	0.11	0.10	0.00
	C_{org} (%)	AS	3	5	4	2.15	–0.59		0.02	0.77	1.62	1.30	0.10
		NHS	3	5	4	2.27	–0.72		0.02	0.76	1.61	1.24	0.14
		WHS	3	5	4	2.56	–0.58		0.04	0.73	1.70	1.49	0.05

AS – acidic sites; HNS – nutrient-rich highland sites; WHS – waterlogged highland sites; CF – clay fractions; BS – base saturation; AG – approximation groups

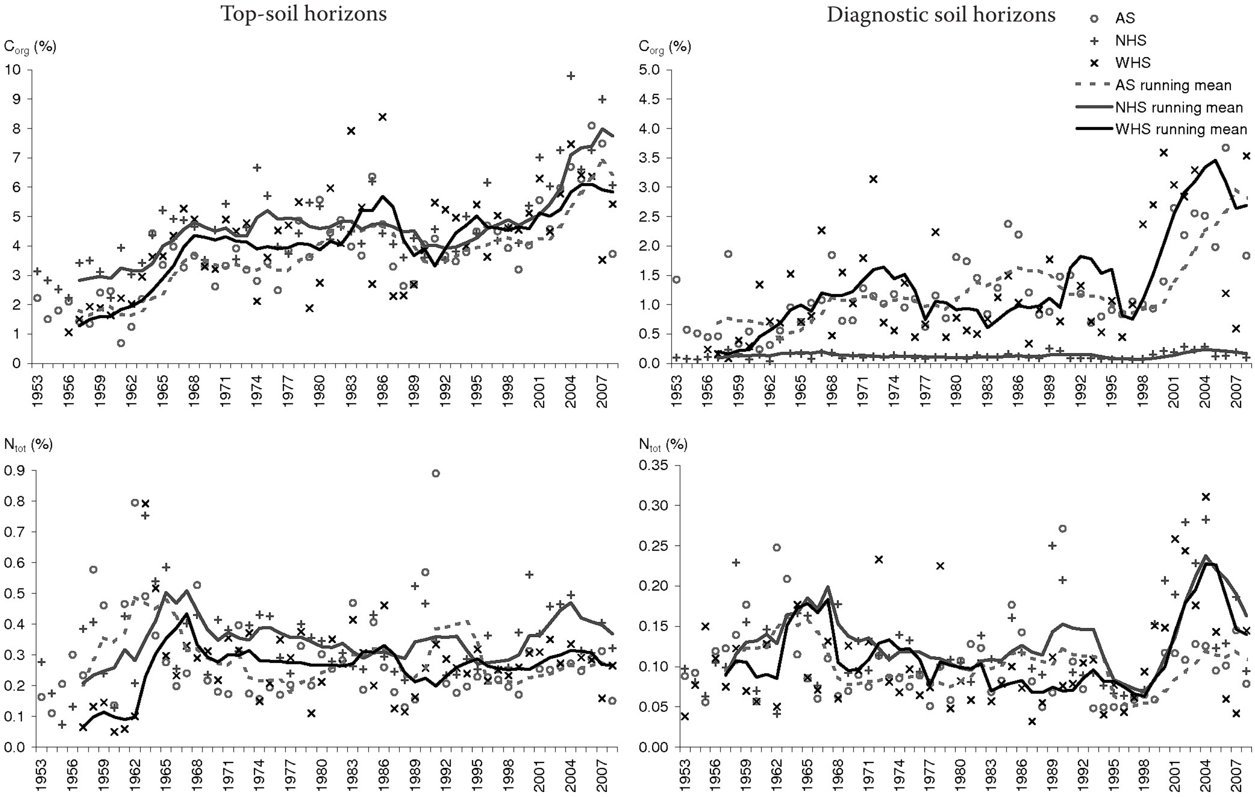

Figure 3. Fluctuations of 5-year running means of the soil organic carbon (C_{org}) and total nitrogen (N_{tot}) at acidic sites (AS), nutrient-rich highland sites (NHS), and waterlogged highland sites (WHS)

agents among the investigated horizons. However, ANOVA indicated that even different values of the soil horizons properties signalize their mutually different behaviour (Table 3).

Predictions of substrate properties were not significantly influenced by random value deviations. The values of CF and CaO were more predictable at ASs and NHSs, while the values of MgO were more predictable at WHSs. Physicochemical soil properties were predictable within a period of 3–5 years, C_{org} and N_{tot} mostly within five years. Eq. (1) usually allowed a statistically significant prediction at an interval of 3–5 years. Eq. (3) usually allowed a statistically significant prediction at an interval of 4–5 years. Eq. (4) indicated most predictions at a wider period of 4–7 years.

Similar regression equations in total contents of nutrients, pH, BS, and C_{org} indicated that in selected forest FEUs, these soil properties had parallel development trends. However, different prediction periods in total contents of nutrients and physicochemical parameters indicated that their development could be influenced by external stimuli in different ways. The same value prediction periods in different parameters in different horizons and FEUs indicated close response of soils to the influence of external factors. Different regression equations of the content prediction of CF and N_{tot} in TSHs and DHs indicated the occurrence of permanent differences in the development of soil horizons mainly in waterlogged soils. The differences between equations indicated the occurrence of different trends in the soil development.

Table 3. Statistical tests of quality in regression prediction of selected soil properties (bold statistical signification differences at $P < 0.05$)

Quality	ANOVA			Statistical testing	
	horizons	calculations	feedbacks	*F*-test	*t*-test
CF	**12.58**	0.12	0.01	1.24	–1.07
pH/H_2O	**37.43**	0.34	0.02	1.05	–40.53
pH/KCl	**36.47**	2.00	0.01	1.15	–7.33
BS	0.96	2.33	0.07	1.14	0.02
CaO	0.45	3.62	0.03	2.17	0.00
MgO	5.10	0.28	0.27	1.29	–0.91
N_{tot}	**74.00**	1.03	0.15	1.15	–8.31
C_{org}	**327.12**	**8.63**	1.33	1.27	–0.51

CF – clay fraction; BS – base saturation

The combination of approximation 1 was detected sporadically in fluctuations of pH/H_2O in diagnostic horizons of WHSs. The combination of approximation 2 was detected in three cases of fluctuations of BS and MgO in diagnostic horizons of NHSs, and CaO in diagnostic horizons of WHSs. These soil features were predictable on a short-term basis only. Approximation 3 was detected in 29.2% of the obtained development. Approximation 4 was detected in 62.5% of the obtained development. Medium-term approximations included a total of 91.7% of the obtained development. Changes in soil parameters were most frequently predicted at a period of 5 years. Approximation 3 was usually typical for pH in WHSs and for N_{tot} as well. Approximation 4 was typical for the development of CF, BS, C_{org}, and most fluctuations of CaO, MgO, and some N_{tot}. With respect to the period of 1953–2008, the values of soil clay, physicochemical properties, and total contents of nutrients may increase slightly in the period of 2009–2014, while the values of C_{org} and N_{tot} may slightly decrease (Table 2).

DISCUSSION

Changes in the frequency and methodologies of soil sample processing and changes in performing the field surveys influenced the soil development narrative. As a result of these events, the description of forest soil development in the CR was complicated both in terms of the identification of the right period for predicting soil properties and in terms of the correct description of the relationships between soil conditions and forest ecosystem classification.

Causes of the observed fluctuations in soil properties. Changes in the performance of forest soils field research also had negative influence on the degree of observed time series heterogeneity. Soil sampling in dendrometrical measurement plots was focused on the transitions between surface humus and organo-mineral layers. The research of the forest nutrition is fundamentally focused on the evaluation of population management; it does not deal with soil taxonomy. In NFI data, the method of mixed sampling and the absence of data on some soil parameters made it impossible to check in detail the accuracy of soil type identification. Acidic and waterlogged highland sites include soils predisposed to raw humus accumulation (Coleman *et al.* 2004). Top-soil horizons may have a greater thickness here, so contamination of diagnostic horizons with upper organic material cannot be excluded in NFI sampling. As no similar event occurred in the content of organic substances within nominal NHSs, it can be assumed that within ASs and WHSs the trend of a slight increase in soil C_{org} and decrease in N_{tot} continued. The soil dynamics of WHSs is significantly influenced by the stability of anaerobic conditions. The waterlogging process enhanced carbon accumulation in these soils. Lack of water in the soil causes intensification of acidification and CO_2 release (Satrio *et al.* 2009). In waterlogged soils the dynamics of soil carbon and nitrogen was very closely related but in non-waterlogged soils at NHSs it differed significantly. Relatively low values of C_{org} in soils at NHSs, on a medium-term basis, were followed by fast growth of the N_{tot} content after 1998, which started to strongly resemble the dynamics of nitrogen in soils at WHSs. Such changes in C_{org} and N_{tot} manifest themselves by a decrease in C/N ratio and an increase in biological soil activity. The increase in N_{tot} is a possible consequence of eutrophication. The increase in C_{org} is a possible consequence of humus restoration (Dieleman *et al.* 2010). The slight trend of increase in the content of C_{org} indicated that it might refer to a reliable medium-term prediction but repeated occurrence of unusual values due to the uncertain quality of sampling probably influenced the reduction of the probable development prediction length to five years.

The pH development and changes in the content of MgO proved that the method of FEU mapping influences the indication of the ecological forest character by means of soil properties. The differences in pH development in soils of the selected FEUs were limited due to mapping and classification using indicative forest herbaceous species. The pH development was very similar in the compared FEUs throughout the whole studied period, while the development of total contents of nutrients and BS were sometimes similar and sometimes different. Similarities in the content of nutrients occurred within 1985–1994. Similarities in the BS development in TSHs occurred in 1982–1994, while in DHs they occurred as early as 1968–1983. In the same period, the differences between CaO values in the compared FEUs were larger. Potentially different MgO values were not detected in different FEUs if the classification of sites using forest indicative herbaceous species was not able to distinguish nutrient-poor and nutrient-rich conditions. Such a situation occurred after 1995, when legislative changes in field investigations led to reviews of the mapped ecosystems. Soil MgO is characterized by considerable content diversity even within the same soil type, and its fluctuating content may affect health status of plant communities (Houba *et al.* 1993; Vacek *et al.* 2009, 2013).

Soil properties fluctuation trends. Occurrences of relatively regular fluctuations in the evaluated data indicated that variation in the soil properties could be defined using a periodical function. Nevertheless, random deviations in the development of the same parameters in different horizons and FEUs caused differences in the estimated length of probable prediction. The development in CaO, clay, soil BS, and pH was not negatively influenced by changes in the soil sampling methodology. Unusual deviations in these properties usually occurred within 1953–1971. Relatively balanced sections of the substrate properties development since 1979 indicated that the quality of collected material was already maintained in this period. Decrease in pH and BS was accompanied by a decrease in the content of CaO; increase in the values of BS was accompanied by the increase in the content of CaO. A pair of exponential equations best corresponded to the development of fluctuations of these properties. However, consistency between the horizons was only achieved in the content of CF at WHSs and of C_{org} at ASs and NHSs.

The effectiveness of soil sorption complexes in acidic and/or humic soils primarily, or exclusively, is associated with functional groups of organic matter (Ross *et al*. 2008). Differences in the obtained development of soil clay, BS, and C_{org} among the compared FEUs were the most distinct. Lower values of soil clay and BS, along with higher content of C_{org}, were usually related to nutrient-poor ecosystems, while higher values of CF and BS, combined with lower content of C_{org} usually occurred at nutrient-rich sites. In soils at waterlogged highland sites, the bases were not significantly bound to colloids but to coarser inorganic and organic particles. The CaO content correlated with pH, but not with BS. Insignificant correlations between pH and BS in waterlogged soils indicate that the sorption complex is not the dominant factor of the fluctuations in soil properties. The dominant factor is the stagnating water, which limits the formation of colloids by decomposition and predisposes the ecosystem to acidification. Constant differences in the soil parameter values among the evaluated FEUs predetermine the response of forest soils to external stimuli.

Decrease in BS and the increasing content of C_{org} in TSHs and DHs demonstrate the continuing trend of soil acidification. Enrichment of soil with C_{org} may correspond with particulate organic matter (POM) production. The POM is a labile organic matter pool and is sensitive to management practices (Six *et al*. 2002). Excessive production of POM is naturally related to acidic cold humid conditions. Nevertheless, under the acidic and nutrient-rich conditions of the CR, higher production of POM may be the consequence of low condensation to bigger polymers after the decrease in the content of soil bases (Johnson 2002). Under global climate change, the C_{org} content increase in TSHs and DHs corresponds to the assumption of a growing carbon sink on the one hand, but it may also mean that a sufficient layer of humus is not produced on the soil surface. Instead, the intermediates of its production translocate deeper within the soil profile. The relations between soil BS and C_{org} are potentially powerful indicators of the effect of external factors on soil.

CONCLUSIONS

The fluctuations of substrate soil properties and BS were more influenced by the ecological character of the compared ecosystem units than the N_{tot} fluctuations. Lower values of soil clay, BS, and higher C_{org} usually occurred at acidic sites. Higher values of soil clay, BS, and lower C_{org} usually occurred at nutrient-rich sites. The increase in the content of MgO and CaO usually corresponded to an increase in pH and BS.

The fluctuations in chemical soil property values are indicative of the trends in the response of forest soils to environmental change. Acidic sites seem to be much more sensitive to acidification than nutrient-rich sites. The C_{org} content increased gradually between 1953 and 2008. Changes in this trend are predictable in the period of up to five years using generalized data. Between 2009 and 2014, a slight increase in BS and decrease in C_{org} and N_{tot} may temporarily occur in all forest soils in the CR, which may reduce the exposure of ecosystems to acidification. Inconsistency between the fluctuations of pH, BS, CaO, and C_{org} and increasing content of N_{tot} may, on the contrary, indicate re-acidification of forest soils.

Acknowledgements. The study was supported by the Education for Competitiveness Operational Program – the European Social Fund (Project CZ.1.07/2.3.00/20.170 of the Ministry of Education, Youth and Sports of the Czech Republic) and by the Project PrF_2013_024 of Palacky University in Olomouc and Ministry of Agriculture of the Czech Republic, programme QJ – Comprehensive sustainable systems in agriculture 2012–2018 "CSS" (Identification code QJ1320040).

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Received for publication September 4, 2013
Accepted after corrections May 22, 2014

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