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CATENAS OF GRAIN SIZE AND CHEMICAL FOREST SOIL PROPERTIES IN OUTER WESTERN CARPATHIANS OF THE CZECH REPUBLIC CHARACTERIZED BY PRINCIPAL COMPONENT ANALYSIS

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Abstract

More frequent occurence of hillwashes in altitudinal-differentiated landscapes causes changes of relationships among terrain, bedrock and soils. The aim of the study was to characterize catenas of the terrain-bedrock-soil relationships by PCA of forest soil properties generalized into 2 × 2 km grid in Outer Western Carpathians (OWC) of the Czech Republic. The spatial relationships of the soil catenas with terrain and rocks were verified by ANOVA. Typification of the catenas was carried out by frequencies in the presented terrain and bedrock types according to biogeographical division system. Base saturation, CaO and P_2O_5 divide forest soils in OWC to ten catenas. The catenas characterized by moderate correspondence of soils and bedrock are concentrated in Outer Depressions, while catenas with moderate correspondence of soils and terrain are concentrated in Flysch Range. The Outer Carpathian Depressions are covered predominantly by floodplains, flat waterlogged, loess-covered and luvic hillycountries (67% of the grid). The Flysch Range is covered predominantly by proluvial slopes, broken hillcountries and submountain to mountain slopes (65% of the grid). The Floodplains, broken nutrient-medium hillycountries and mountain slopes have medium to marked soil horizon properties heterogeneity. The flat landforms, proluvial and submountain slopes have moderate soil properties heterogeneity. The statistical significant differences between values of properties at A and B horizons suggest rate of an surface matter translocation effect on the soil catena heterogeneity.

Keywords: geological environment, hillwashes, soil heterogeneity, soil base saturation

INTRODUCTION

Soil catena is a series of co-evolved soil units down a slope. The co-evolved soils are characteristic by similar grain size and chemical composition. Soil catena boundaries are delimited by transitions among various terrain or parent-material (bedrock) types. Both Earth̓s surface terrain and bedrock form geological environment structures (Pietrzyk-Sokolska, 2012). Spatial relationship of geological environment and soil catenas is not homogeneous. Different spatial relationships lead to different correlations of soil properties in areas with various geological environment (Bautista *et al.*, 2011). The distinction of soil catenas conditioned by terrain, or likewise, by the bedrock is based on the soil property value differences (Villela *et al.*, 2013). Geomorphological or bedrock effect on soil grain and chemical composition was not statistically distinguished yet. However, similar soil properties can suggest natural boundaries of the geological environment effect on catena development (Costantini *et al.*, 2007).

The catena is formed under homogeneous processes of precipitation, infiltration, runoff and evaporation, which tend to erosion prevailing at upper slope parts and to accumulation prevailing at the slope (Sommer and Schlichting, 1997). Catena development culminates when erosion and accumulation processes achieve dynamical equilibrium (Brown *et al.*, 2004). Borders of the catenas run along catchment divice, however, they are not only geomorphological, but also geochemical. The geochemical borders occur along different rock weathering lines (Khomo *et al.*, 2013). The using of geomorphology does not enough itself for survey on catena development, but the development can be derived through using of similarities in chemical composition between soil and bedrock. The comparison of chemical composition similarities between soil and bedrock suggests, if soil could be developed *in-situ*, or if it could be a sediment (Dempster *et al.*, 2013).

Although, slope inclination is the most frequent precondition for soil catena development, water and sediment transport along inclination disturb relationship between slope and catena. The similarity of chemical composition between slope sediment (hillwash) and bedrock suggests that a transport down a slope is unsignificant and slope inclination does not influence catena. On the contrary, difference in chemical composition between hillwash and bedrock confirms slope influence (Schaetzl and Anderson, 2005). Even so, the hillwashes are not included as catena development component (Bern *et al.*, 2011). Hillwashes modify soil catena forming the most in young mountain systems, where mark slope movements are concentrated (Pánek *et al.*, 2013). Altitudinal gradients of soil properties changes are characteristic by decrease of clay content as well as base saturation and by skeletic, soil moisture, porosity, acidity and humus content increase (Lin, 2006). On the other hand, unsignificant differences at chemical composition of forest soil edaphic categories in the Moravian-Silesian Beskids suggest that the broken terrain conditioned representation of soil groups more than bedrock chemical composition (Holuša, 1995). However, in comparison to the Beskids, surrouding Moravian Gate is characterized by several bedrock types, little ragged terrain, but potentially very variable soil catenas (Tyráček, 2011).

This study is focused on statistical distinction of terrain or bedrock effects on soil catenas between lowland and mountain systems. Geological environment inprints signatures into soils, so that soil properties are organized into clusters of similar spatial relationships (Dempster *et al.*, 2013). Soil grain size and chemical properties are basic signatures of the geological environment (Filzmoser *et al.*, 2009). The soil catenas were demarcated from soil properties statistical clusters. Geological environment structure effect on soil catenas was distinguished through comparison of variances between soil horizon properties inside catena and mean values at terrain or bedrock type range. The unsignificant variance between soil catenas and terrain or bedrock suggested close correspondence of soils to geological environment. The higher correspondence of soil catena to terrain than to bedrock indicated transported soil. The higher correspondence of soil catena to bedrock than to terrain indicated untransported soil.

MATERIALS AND METHODS

The statistical characteristics of relief and bedrock effects on soil was divided to exploratory and comparison analysis. We concentrated on forest soils in Outer Western Carpathians (OWC) of the Czech Republic because of preserved natural spatial relationships to geological environment covered by hillwashes predominantly (Sitková and Kunca, 2008). Examined forest soil properties consisted of geological and soil environment characteristics. The geological environment characteristics were used for definition of the investigated area and for assessment of the signatures at catenas. The soil environment characteristics were used for demarcation of soil catenas.

Exploratory analysis of the soil properties contained overlay and multivariate analysis of point field from sampled pits (Dempster *et al.*, 2013). The sampled forest soil pits were characterized by statistical selection of potentially most significantly correlating soil properties. Top-soil A-horizons and subsurface B-horizons were distinguished at sampled forest soil pits (FAO, 1998). The exploratory analysis was based on B-horizon properties. The A-horizon properties were used for the exploratory analysis of the sampled pits in cases of soil groups without developed diagnostic horizon. Soil catenas were defined by principal component analysis (PCA).

Comparison analysis was focused on assessment of correspondence between geological environment and soil catenas. Mean values from A- and B-horizons at geological environment particular types and at penetrating soil catenas were compared. A- and B-horizons naturally differentiate each other by influence rate of environmental properties. Properties of A-horizons more closely correspond with properties of climate and vegetation, whereas B-horizons more closely correspond with bedrock (Němeček and Kozák, 2003).

Investigated area

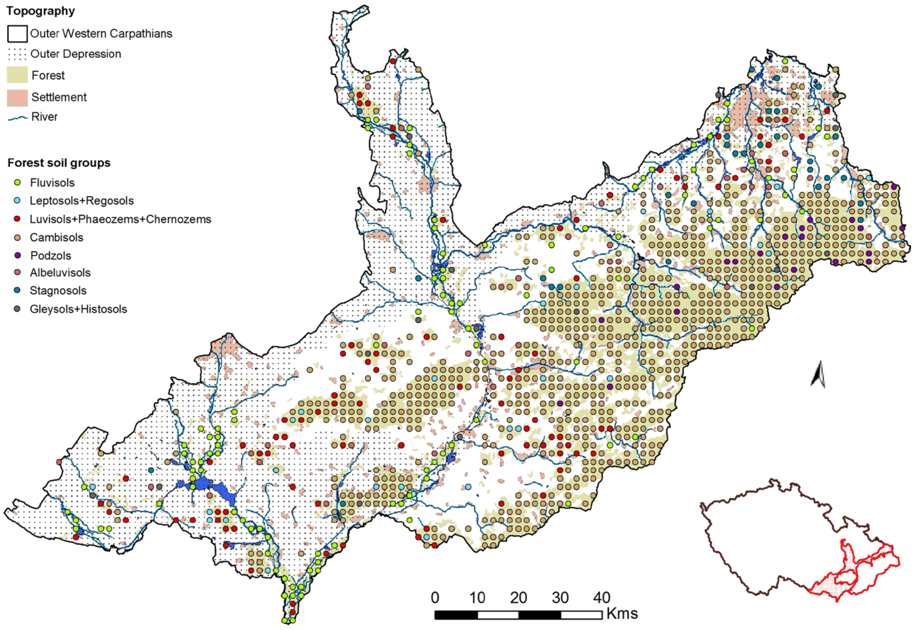
The OWC differs from the surrouding geological units of the Bohemian Massif, epi-Hercynian Depressions and Inner Carpathians mainly by larger proportion of active slope movements (Niklińska and Klimek, 2011). The surface substrates are represented by 97% of hillwashes in Western Carpathians. Only 3% of soils were formed from untransported mantle rock. The deposited surface substrates are composed by 10% of riverine sediments, 18% of eolian sediments, 65% of mixed hillwashes, 2% of debris and 2% of glacigenic or glacimorphic sediments (Šály, 1986). The proportion of forest soil groups markedly differs between Outer Depressions and Flysch Range in OWC. The Fluvisols (34%), Cambisols (31%) and Albeluvisols (16%) dominate at inventory 2 × 2 km grid in Outer Depressions of the CR. Leptosols and Podzols miss here in contrast to Flysch Range. Cambisols (88%), which are marginally inclused by Albeluvisols (2%), Podzols (2%) a Luvisols (3%), outweight in Flysch Range of the CR markedly (Tab. I) (Jankovská and Štěrba, 2007).

Data

The forest soil properties were examined through polygonal and point data. Outer Western Carpathians in the CR cover 12,113 km^2 (15.4%). The Outer Depressions in the CR cover 5730 km^2 (47.3%) and the Flysch Range covers 6383 km^2 (52.7%). The forestland of Outer Western Carpathians in the CR is 36.8%, but majority of the forests (71.9%) is concentrated in Flysch Range, whereas only 28.0% of the forests occur in Outer Depressions. The polygons of Outer Depressions and Flysch Range were taken from vectors of the geomorphological division of the CR (Mackovčin *et al.*, 2009). Geological environment was characterized by types of terrain and bedrock. The terrain and bedrock were taken from polygonal GIS

I: *The proportion of soil groups at forest inventory grid 2×2 km in Outer Western Carpathians of the Czech Republic (%).*

Soil group	Outer Depression	Flysch Range	Total
Anthrosols	2.34	0.26	0.79
Leptosols	-	0.79	0.59
Fluvisols	34.38	1.84	10.02
Chernozems	0.78	-	0.20
Luvisols	9.77	3.41	5.01
Albeluvisols	15.63	2.36	5.70
Cambisols	30.86	88.06	73.67
Podzols	-	2.23	1.67
Stagnosols	3.91	0.92	1.67
Gleysols	2.34	0.13	0.69



1: *The occurence of forest soil groups in Outer Western Carpathians of the Czech Republic generalized to grid 2 × 2 km.*

of biochoral classification in the CR (Culek and Grulich, 2009). The 18 terrain types and 31 generalized bedrock types occur in the CR, but 13 terrain types and 22 bedrock types occur in OWC (Culek *et al.*, 2005). Plains (23.5%), broken plateaus (22.2%), slopes (14.5%), uplands (11.2%) and wide floodplain (9.2%) are the most common terrain types in the CR. Loess (25.2%), marl flysch (24.8%), sandstone flysch (12.9%) and prevaily loam floodplain deposits (11.0%) are the most common bedrock types here.

Soil environment was characterized by soil associations and point field of the sampled pits. Soil association is a set of dominant and associated or inclused soil groups (Sedláček *et al.*, 2009). The polygonal GIS of forest soil associations was created by generalized overlay between environment and forest types edaphic categories at Forest Management Institute Data Information Centre (FMI-DIC) database (Macků and Homolová, 2007). The forest soil associations and field of the sampled pits were taken from database of Regional Forest Development Plans at the FMI-DIC. The point field includes 2736 pits sampled in 1953–2010 during state pilot surveys of forest soils (Samec *et al.*, 2014). Ten soil groups were sampled from OWC in the CR (Fig. 1). Geological environment of sampled pits was obtained by intersection of altitude, aspect and slope from DEM 10 × 10 m. Horizons of the sampled forest soils were characterized by grain size, sorption cation exchange capacity (CEC) and base saturation (BS), C_{org}, N_t and by contents of bound macroelements (Fe_2O_3, Al_2O_3, MnO, CaO, MgO, K_2O, P_2O_5) (Vanmechelen *et al.*, 1997). Soil groups were classified according to WRB-ISSS-ISRIC (Michéli *et al.*, 2007).

Overlay analysis

Overlay analysis helped for basic characteristics of forest soil proportions in Outer Western Carpathians and to assessment of representativeness of their sampling. The basic characteristics of forest soils in the investigated area was carried out by overlays of polygonal GIS of the geological environment and soil associations. The representativeness of forest soil sampling was verified by linear regression between frequencies of the pits and total proportions of the soil associations at $P < 0.05$.

Multivariate analysis

Multivariate analysis of soil environment was used for statistical selection of potentialy the most significantly correlating properties and for demarcation of the soil catenas. The statistical selection used a dimensionality reduction effect for elimination of properties with dissimilar differences in values. It was carried out by a series of principal component analysis for grain and element latent vectors (LV-PCA), factor analysis (FA) and cluster analysis (CLU). The LV-PCA detected unadvisable auto-correlations among soil properties with same units. Intersection of FA and CLU was used for indication of mutually correlating properties at component loads of the latent roots > 0.55 (Thalib *et al.*, 1999). The soil catenas were defined according to PCA component score (CS-PCA) similarities in point field of the pits. CṠs were calculated for the selected correlating properties of the pits at ortogonal latent roots including > 50% of the total variance (Jackson and Chen, 2004). Known differences in values of the selected soil properties among various soil groups, soil horizons and altitudes (Pelíšek, 1973) were used for characteristics of the most significant identified components between FA and CS-PCA. Corg and Nt the most differ vertically between various horizons in soil body. BS, pH a CaO the most differ between various soil units and CEC as well as grain size differ at various altitudes the most (Borůvka *et al.*, 2007). The characterization of the catenas was carried out by frequencies in the presented terrain and bedrock types according to Culek *et al.* (2005).

Comparative analysis

Statistical comparison was used for correspondence and contradictory analysis. The correspondence was obtained by comparison of similarities between geological environment structures and penetrating catenas. The contradictory was obtained from differences among forest soil group properties inside particular catenas (Filzmoser *et al.*, 2009). The comparative analysis was carried out by analysis of variance (ANOVA). The geological environment was characterized by aritmetic averages of the compared properties. The catenas were characterized by weighted averages of the forest soil properties at the geological structure. Sporadic cases of statistically significant differences in the soil properties indicated moderate heterogeneity of soil environment. An occurence of statistically significant differences in more than a half of the selected soil properties number indicated medium heterogeneity and all statistically differentiated soil properties indicated mark heterogeneity of the soil environment.

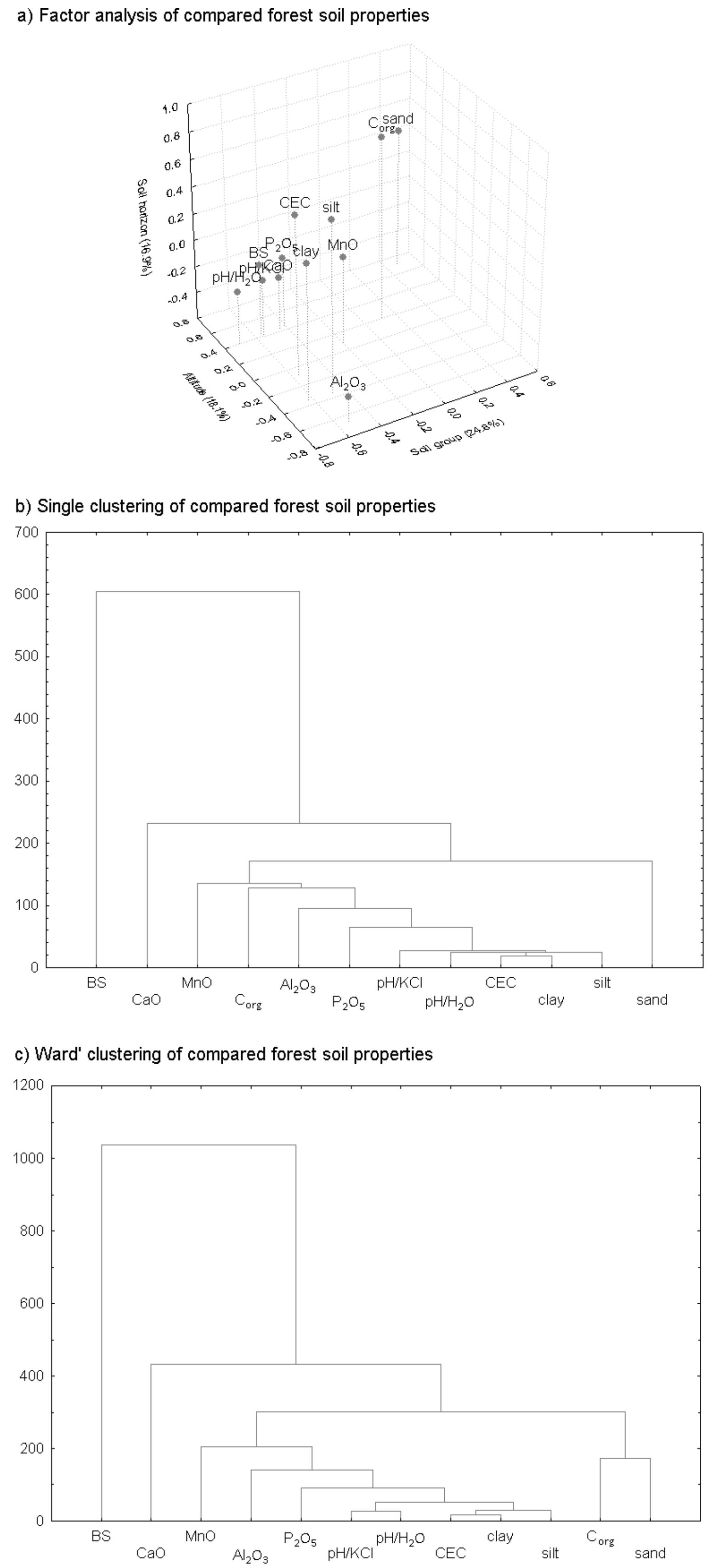
Projection

The basic unregular soil group point field of input sampled pits and final soil catenas were generalized and projected at ArcGIS 10.3 by Spatial Analyst processor. The polygons of forests and forestless, rivers and settlements were taken from database DATA200 provided by State Administration of Land Surveying and Cadastre. Generalization of the basic unregular point fields into 2 × 2 km grid was carried out by method of nearest neighbour of a centroid (Jankovská and Štěrba, 2007). The classification of both projected variables are qualitative. A colour scale of soil groups was taken according to convergent classification of the WRB-ISSS-ISRIC soil association matrices (Sedláček *et al.*, 2009). A colour scale of the final catenas was composed as divergent (Dempster *et al.*, 2013).

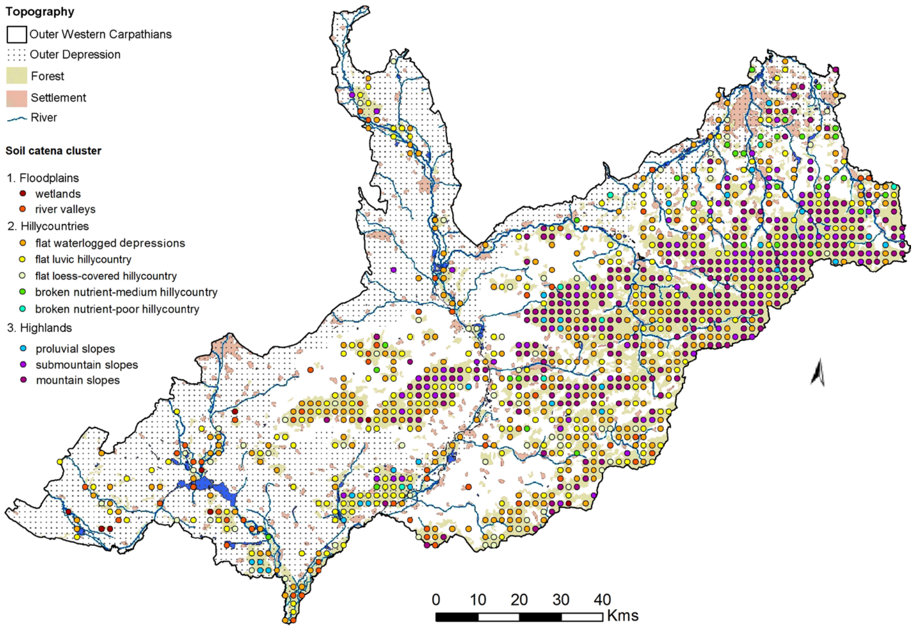
RESULTS

Forest soils in Outer Western Carpathians of the CR have occurence concentrated on slope reliefs (37.7%), at highland altitudes (15.9%), on broken plateaus (12.5%) and on bedrock of sandstone flysch (40.8%) and marl flysch (36.3%). Outer-Carpathian forests in the CR the most cover steep slopes (49.8%), marl uplands (9.8%), but also floodplains (12.8%). Cambisols and Fluvisols occur almost in all forested parts. On the contrary, Gleysols, Phaeozems and Anthrosols occur rarely and together occur only in floodplains (2.9%). Cambisols are dominant totally in eight terrain types (47.5–100.0%). Fluvisols are dominant in wide floodplains (82.9%), but Cambisols prevail already in river terraces (72.0%), while Fluvisols (12.5%) and Chernozems (10.4%) are represented very less. Flat plateaus and uplands have dominant Luvisols (63.3%), while polygenetically loamy flat uplands as well as marl uplands are characterized by dominant Albeluvisols (38.4–47.8%). Cambisols are dominant from accumulative plateaus to highlands, where they occur entirely.

In forests of Outer Western Carpathians in the CR, the 64 soil units were sampled totally. The frequency of the sampled soil associations statistically significantly corresponds with total propotion in OWC ($r = 0.98$). Significantly proportional sampled soil units include Calcaric Leptosols, Haplic Phaeozem, Alumic Albeluvisol, three types of Fluvisols, two types of Luvisols, eight types of Cambisols, two types of Podzols and three types of Stagnosols. Haplic units were ordinarily the most often sampled soil bodies. The Fluvisols occur at association Haplic – Stagnic – Gleyic ordinarily. The Stagnosols occur at association Haplic – Luvic – Albic ordinarily. Haplic and Dystric Cambisols are the most proportioned types of Cambisols (16.8% of all pits). Skeletic Cambisols (2.3%) are more frequent than Eutric Cambisols (2.1%). Luvic Cambisols have balanced proportion



2: *The exploratory analysis of correlated forest soil properties in Outer Western Carpathians of the Czech Republic.*



3: *Occurence of the multivariate soil catena clusters in Outer Western Carpathians of the Czech Republic.*

with Ferralic Cambisols. Haplic Podzols were sampled more than Entic Podzols. The grain classes sand, silt and clay, base saturation and nutrient contents C_{org}, CaO, MgO, P_2O_5 a macroelement Al_2O_3 are mutually the most significantly correlating properties of the compared soil bodies (Fig. 2). Differences of the selected soil properties values are the most conditioned by a soil group (24.8%). The highest component loads have sand content, C_{org} a P_2O_5 (Tab. II). Only two the most significant latent roots divide the analysed pits into ten multivariate clusters. The clusters were divided predominantly due to the soil properties values variance among compared soil groups (> 30%) and among compared soil horizons (> 16 %) (Fig. 3). The most frequent forest soil catenas in OWC are low and medium deluviums (49.2%), broken hillycountries (17.5%) and broken highlands (13.2%).

II: *Intervals and mean values of soil catena cluster morphometrical properties and proportions (%) of the sampled soil pits of Outer Western Carpathians in the Czech Republic.*

Cluster	Altitude (m a.s.l.)	Mean altitude (m a.s.l.)	Slope interval (°)	Average slope (°)	Aspect (°)	Outer Depression	Flysch Range
wetlands	170–563	270	0–58	14	58	1.92	0.09
river valleys	150–878	325	0–65	14	123	11.32	3.28
flat waterlogged depression	150–1042	407	0–68	18	143	22.47	16.19
flat loess-covered hillycountry	150–788	336	0–52	12	133	11.15	4.53
flat luvic hillycountry	151–879	374	0–78	17	149	22.30	10.78
broken nutrient-medium hillycountry	159–845	385	0–69	18	154	5.23	2.04
broken nutrient-poor hillycountry	154–1004	502	0–46	17	193	2.44	1.30
proluvial slopes	151–1144	392	0–74	21	172	9.06	3.33
submountain slopes	163–1272	590	0–90	29	170	4.01	14.38
mountain slopes	170–1196	597	0–77	29	178	10.10	44.08

Forest soil catenas in Outer Western Carpathians form clusters of floodplains (wetlands and river valleys) (5.5%), five clusters of flat or broken hillycountries (40.8%) and three clusters of steep highland slopes (53.7%) (Fig. 3). The identified soil pits clusters have concentration of occurence either in Outer Depressions or in Flysch Range. Any cluster does not occur either in the Depressions or in Flysch Range entirely. The clusters of wetlands, river vallyes and flat hillycountries are concentrated in Outer Depressions. Little frequent catenas of broken hillycountries to proluvial slopes are else more proportional in the Depressions, but their total number predominants in Flysch Range with it builds interface. The Flysch Range is demarcating by the most proportional catenas of flat waterlogged depression, flat luvic hillycountries and submountain to mountain slopes. Floodplain to hillycountry catenas in Outer Depressions include 69.2% of pits, whereas they include only 34.9% of pits in Flysch Range. Dominant catenas of Flysch Range include almost 88.8% of pits. The intervals of altitudes and slopes of all demarcated catenas are similar markedly. They differ by maximum values of the sampled soil unit morphometrical features. Wetlands were sampled upto 563 m a.s.l. River valleys were sampled upto 878 m a.s.l. The catenas broken nutrient-poor hillycountry, submountain and mountain slopes have average altitude > 500 m a.s.l. and highest occurence > 1000 m a.s.l. Herewith, flat luvic hillycountries, proluvial slopes, submountain and mountain slopes occur in terrain with maximum slope > 70°, although only proluvial and (sub)mountain slopes have average slope of occurence > 20°. Soil units of the flat loess-covered hillycountries and of the floodplain cluster have smallest average slope of the sampling and lowest average altitude (Tab. II).

The catena wetlands covers associations of Fluvisols (60.0%), Phaeozems (20.0%) and Chernozems (20.0%), but only Fluvisols (42.8%) and Leptosols (57.2%) were sampled. Lime bedrock of wetlands covers >23% from total area of the forest soils. The catena river valleys covers floodplains and stream valleys in flat hillycountries with predominant hillwashes. Plain terrains on > 30% from a total area, presence of sandstone flysch < 10% only and of marl flysch < 40% from a total area and predominant Fluvisols (32.8%), Cambisols (30.5%) and Luvisols (13.3%) are differential features of the river valleys. The cluster of hillycountries includes three catenas of flat hillycountries and two catenas of broken hillycountries. In flat hillycountries, the forest soils occur on waterlogged, luvic and/or loess sites. In broken hillycountries, the forest soils occur either on nutrient-poor or on predominantly zonal nutrient-medium sites.

The catena flat waterlogged depressions includes transitions between river valleys and flat luvic hillycountries. The catena flat waterlogged depressions include < 18% of flat depressions where Fluvisols, Cambisols and Albeluvisols predominante. Fluvisols in depressions have average BS > 90%. Carpathian flat waterlogged depressions are built by > 40% of marl flysch and < 20% od sandstone flysch. The catena flat luvic hillycountries covers similar terrains as waterlogged depressions, but it is characteristic by proportion of sandstone flysch 20–24% from total area, by proportion of marl flysch < 40%, by occurence of fluvial (gravel) sands > 7%, by proportion of Stagnosols and Gleysols 6%, by proportion of Phaeozems + (Albe) Luvisols 27% and average BS of Fluvisols < 70%. The catena flat loess-covered hillycountry occur predominantly in central parts of flat hillycountries without isolated peaks. Here, flat terrains cover < 25% of forest soil area. The occurences of loess > 8% and marl flysch > 40% from the total area, the occurence of sandstone flysch < 15% from the total area vice versa, and common proportion of Fluvisols (17.6%) and Luvisols (37.5%) higher than occurence of Cambisols (24.7%) are differentiating features of the catena loess-covered hillycountry.

The catena broken nutrient-medium hillycountry covers terrain from flat hillycountries to margins of highlands. Globally, it is characteristic by balanced propotion of flat terrains and slopes where loesses cover 10–15%, sandstone flysch covers 24–40% and waterlogged depressions 36% of the total area. In broken nutrient-medium hillycountries, Stagnosols (27.9%), Luvisols (21.9%) and Cambisols (21.1%) predominant (Tab. III). On the contrary, the broken nutrient-poor hillycountries were demarcated in flat hillycountries divided by ridges. Here, mark ridges covers > 7% and sandstone flysch > 40%, but residual loesses occur < 10% from the total area. For the broken nutrient-poor hillycountries, Histosols > 3% and Cambisols (34.4%) with BS < 10% are characteristic. Highest altitudes of Outer Western Carpathians are formed by steep slopes of broken highlands. The foothill of Carpathian highlands is locally formed by proluvial slopes. The proluvial slopes are concentrated predominantly on south-eastern foothill of Flysch Range. They are covered by Histosols (1.7%), Regosols (0.8%), Fluvisols (3.4%), Gleysols (2.5%), Stagnosols (1.7%), Cambisols (70.3%) and Podzols (7.7%).

Average BS of Cambisols 30–50% is differentiating property of forest soils on the proluvial slopes. The submountain slopes occur along perimeters of mountain massives with small-scale occurences of Chernozem and Albeluvisol associations > 5%. Submountain slopes are characteristic proportions of sandstone flysch in forests > 65% and marl flysch < 20%. Cambisols on submountain slopes have average BS > 20% and Podzols < 11%. Mountain slopes cover medium upto peak parts of mountain massives. The proportions sandstone flysch in forests > 65% and marl flysch > 25%, residual occurence of Albeluvisols < 5% and simultaneously average BS of Cambisols < 20% are their differentiating features.

A pertinence of sampled forest soil to multivariate catena was assessed either by occurence of characteristic soil group or by characteristic values of BS, grain size and Al_2O_3 content. The wetlands or river valleys are the most clean-cut catenas which occurence is conditioned by floodplain. Soil catenas flat loess-covered hillcountries as well as broken nutrient-medium and/or nutrient-poor hillycountries are differentiable by occurences of unique soil groups. Occurence of Chernozems is typical for the flat loess-covered hillycountry, the occurence of Phaeozems is typical for the broken nutrient-medium hillycountries and absence of Phaeozems and Albeluvisols is characteristic in the broken nutrient-poor hillycountries. Another soil catenas are differentiable predominantly by characteristic intervals of the occuring soil association properties (Fig. 4).

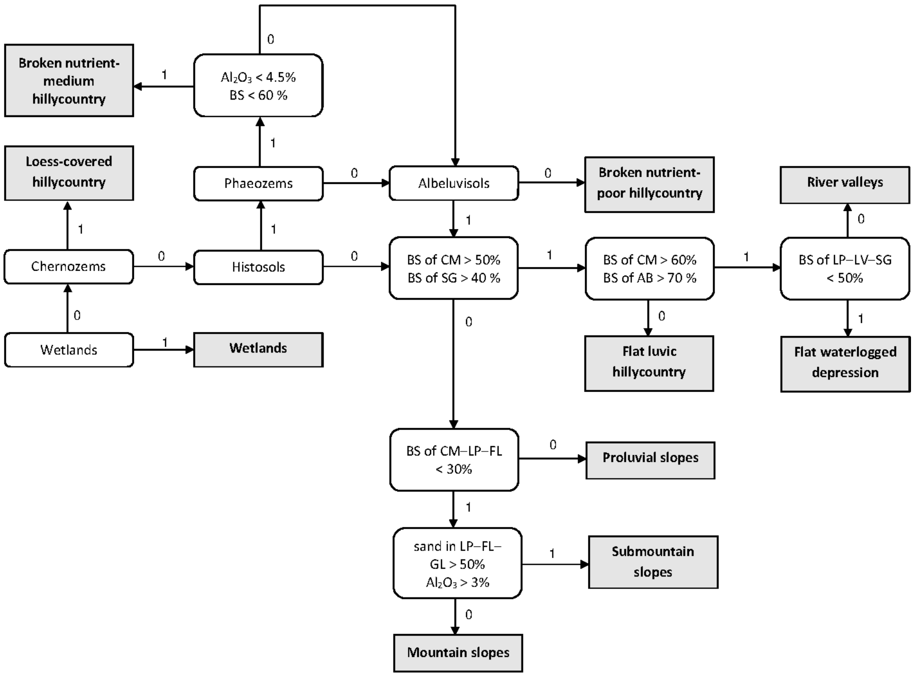
The individual catenas have significantly similar properties of occuring soil groups. The proluvial slopes, submountain slopes, nutrient-medium hillycountries and flat waterlogged depressions have statistically homogenous soil properties. The flat luvic hillycountries, loess-covered hillycountries, nutrient-poor hillycountries and mountain slopes have moderately heterogeneous grain class or nutrient content of the occuring soil groups. Soil horizon properties heterogeneity is statistically more significant than heterogeneity of the selected properties of various soil groups. Major part of the catenas features by different grain size between soil horizons. The BS and P_2O_5 content differ between soil horizons at majority of the hillycountry catenas the most. The flat luvic hillycountries, loess-covered and nutrient-medium hillycountries, proluvial slopes to submountain slopes have moderately heterogenous properties

III: *The proportion of forest soil groups at soil catena clusters (%).*

Soil group	**wetlands**	**river valley**	**flat waterlogged depression**	**flat loess-covered hillycountry**	**flat luvic hillycountry**	**broken nutrient-medium hillycountry**	**broken nutrient-poor hillycountry**	**proluvial slopes**	**submountain slopes**	**mountain slopes**
Anthrosols	-	-	-	-	-	1.40	1.81	3.65	-	-
Histosols	-	-	-	0.68	-	-	3.81	1.72	-	-
Leptosols	57.18	12.78	0.78	0.68	1.80	7.72	12.99	4.26	4.30	2.18
Regosols	-	-	-	-	-	1.54	11.16	0.83	-	-
Fluvisols	42.82	32.83	13.91	17.56	2.89	6.13	-	3.35	2.46	0.96
Gleysols	-	3.96	1.59	5.49	2.68	6.23	-	2.52	0.60	-
Stagnosols	-	3.57	1.75	7.34	3.28	27.93	14.95	1.71	1.24	2.86
Cambisols	-	30.46	75.76	24.72	62.49	21.05	34.43	70.29	71.88	84.98
Chernozems	-	-	-	1.23	-	-	-	-	-	-
Phaeozems	-	2.36	0.38	0.47	12.00	-	-	-	-	-
Luvisols	-	13.25	3.50	37.49	9.43	21.88	3.79	-	-	-
Albeluvisols	-	0.79	2.06	4.35	5.42	6.12	-	3.95	3.62	0.46
Podzols	-	-	0.26	-	-	-	17.04	7.71	15.90	8.56
Total	0.48	4.97	17.51	5.92	13.19	2.70	1.54	4.53	12.21	36.95

IV: *The classification of horizontal (among soil groups) and vertical heterogeneity (among observed soil horizons) by analysis of variance (**bold** at **P** < 0.05) of the soil catena cluster selected properties.*

Cluster	Body	sand	silt	clay	BS	C_{org}	Al_2O_3	CaO	P_2O_5	Classification
wetlands and river valleys	Soil group	0.66	1.96	1.56	2.26	1.43	0.63	1.02	2.40	Homogeneous
	Horizon	**20.89**	**334.16**	**100.05**	**24.16**	**30.99**	**13.80**	**6.03**	**10.99**	Markedly heterogeneous
flat waterlogged depression	Soil group	3.73	0.32	0.64	0.50	1.61	2.49	1.07	**7.03**	Moderately heterogenous
	Horizon	**15.35**	4.36	**7.21**	**14.46**	6.20	2.71	1.87	**22.70**	Moderately heterogenous
flat loess-covered hillycountry	Soil group	**8.74**	2.77	3.42	0.26	2.68	3.73	5.61	**37.25**	Moderately heterogenous
	Horizon	1.63	5.27	0.01	3.29	**29.00**	2.70	0.18	**28.09**	Moderately heterogenous
flat luvic hillycountry	Soil group	1.26	0.40	0.33	0.86	1.64	0.46	**28.08**	2.05	Moderately heterogenous
	Horizon	**151.41**	**24.51**	0.01	0.12	**48.82**	0.46	**6.29**	**12.02**	Moderately heterogenous
broken nutrient-medium hillycountry	Soil group	2.33	0.32	0.60	1.60	0.86	1.03	0.81	2.91	Homogeneous
	Horizon	**153.41**	**141.17**	0.48	**48.17**	0.05	1.15	3.20	**12.33**	Moderately heterogenous
broken nutrient-poor hillycountry	Soil group	0.19	0.55	0.19	1.43	**616.30**	1.84	0.44	**27.82**	Moderately heterogenous
	Horizon	**128.75**	**616.41**	2.45	**11.88**	**12.20**	**25.34**	4.98	9.34	Mediumly heterogeneous
proluvial slopes	Soil group	3.83	3.56	1.91	0.92	0.94	1.38	1.65	0.66	Homogeneous
	Horizon	**123.51**	**157.30**	0.03	5.36	3.70	**15.31**	4.57	4.89	Moderately heterogenous
submountain slopes	Soil group	2.60	0.63	2.12	0.68	0.76	0.63	3.21	2.83	Homogeneous
	Horizon	**21.27**	**15.08**	2.12	1.69	**6.15**	0.20	0.07	0.16	Moderately heterogenous
mountain slopes	Soil group	0.47	0.14	**5.15**	1.41	1.44	1.01	0.81	**10.21**	Moderately heterogenous
	Horizon	**9.70**	**9.72**	**7.55**	**13.66**	1.26	**19.74**	0.92	2.28	Mediumly heterogeneous



4: *Classification chart of the multivariate soil catena clusters in Outer Western Carpathians through soil group properties. 1 – Agreement; 0 – Disagreement.*

between soil horizons. The broken nutrient-poor hillycountries and mountain slopes have mediumly heterogeneous properties between soil horizons. River valleys differ from the other clusters by all properties between soil horizons markedly heterogeneous (Tab. IV). The terrain or bedrock types do not significantly condition differences in soil properties among the particular catenas. Differences among individual catena soil properties are predominantly conditioned by BS, CaO and P_2O_5 contents heterogeneity (Tab. V).

DISCUSSION

Characteristic values of base saturation and contents of CaO and P_2O_5 divide forest soils in Outer Western Carpathians to ten catena clusters from floodplains to mountains. Differences of BS, CaO and P_2O_5 are higher between individual soil horizons than among particular catenas. Terrain and bedrock divide differences among individual soil group properties inside individual clusters only. The compared geological environment structures do not significantly influence differences in soil properties among the demarcated catenas. The discussion about multivariate analysis of forest soil properties in Outer Western Carpathians is concentrated on indication of soil body pertinence to the defined catenas and potential spatial consequences between geological and soil environment (Brown *et al.*, 2004; Costantini *et al.*, 2007; Bautista *et al.*, 2011).

Multivariate classification of selected potentially correlating soil properties defines variously fertilited and broken soil catenas. Each soil catena occurs at specific interval of terrain morphometric features. The site conditions, where forest soil properties are more depended on bedrock or where their effects are modified by hillwashes, were discriminated at these limits. Šály (1986) formulated conclusion that hillwashes in Western Carpathians had the most markedly influenced soil catena diversity, whereas Pelíšek (1973) and Holuša (1995) assessed that Carpathian soil catenas had able to the most markedly formed by slope and altitude. Although, separated soil group classification is not enough for complex soil catena evaluation (Němeček *et al.*, 2001), fusion of the soil group classification and its properties indicates terrain effect on soil catena (Macků and Homolová, 2007). Outer-Carpathian altitudinal soil group crossovers are from Stagnosols and Gleysols (150–700 m a.s.l.), peneplain Haplic, Vertic or Eutric Cambisols (150–300 m a.s.l.), hillwash Dystric Cambisols (450–1100 m a.s.l.), Entic Podzols (800–1300 m a.s.l.) upto mountain Skeletic

V: *Analysis of variance (**bold** at **P** < 0.05) of the geological environment signature potential influence on properties in observed horizons of the soil catenas.*

Structure	Horizon	Signature	sand	silt	clay	BS	C_{org}	Al_2O_3	CaO	P_2O_5
Terrain	Top-soil	Environment	0.20	0.04	0.83	0.25	0.01	2.47	1.59	1.61
		Cluster	1.19	0.87	1.31	**3.44**	1.00	2.42	**8.73**	**8.96**
	Subsurface	Environment	0.15	0.15	0.06	0.00	0.48	1.19	0.02	0.21
		Cluster	1.58	1.28	2.43	2.70	1.96	3.01	1.48	0.07
	Total	Environment	0.04	0.00	0.41	0.72	1.18	1.41	1.31	0.95
		Cluster	1.64	1.41	1.64	**5.43**	2.31	2.75	8.41	**7.80**
Bedrock	Top-soil	Environment	0.31	0.10	0.96	0.38	0.01	2.86	1.43	2.42
		Cluster	1.29	0.76	1.56	**4.56**	1.00	2.83	**5.09**	7.40
	Subsurface	Environment	0.14	0.15	0.07	0.00	0.83	1.44	0.00	1.84
		Cluster	**2.04**	**1.50**	**3.62**	**3.76**	1.35	**3.65**	2.92	**3.87**
	Total	Environment	0.04	0.01	0.48	1.34	1.09	1.63	1.67	0.95
		Cluster	**2.27**	**1.76**	2.00	**9.36**	1.56	**3.41**	**8.15**	**7.80**

Podzols (1100–1600 m a.s.l.) and sub-alpine Humic Leptosols (1600–1750 m a.s.l.) (Pelíšek, 1973).

The geological environment effects on soil properties were more little than differences between A- and B-horizon properties, but the bedrock effects on soil properties were moderately more significant than terrain effects. Surface substrate and vegetation cover influence soil properties heterogeneity on altitudinaly undivided terrains the most (Phillips, 2001). Nutrient content at A-horizons of altitudinaly undivided sites is very similar with nutrient content at bedrock, whereas their similarities are less on altitudinaly divided areas due to gravitational movements (Dempster *et al.*, 2013). Substitution of terrain effect by differences between A- and B-horizons of hillwash strata is cause of undistinguishableness among the soil catenas by basic morphometric characteristics. However, the differences among highest values at terrain properties correspond with concentration of soils in individual catenas on various bedrocks and on various relief types (Costantini *et al.*, 2007).

The particular catena is characteristic, on one hand, by unique presence of selected soil groups or their associations, on the other hand, also by unique differences between top-soil and subsurface soil properties. Unique presence of soil groups allows to subsume the sampled soil body in wetlands or flat loess-covered hillycountries only. The classification of the other sampled soil body needs common assessment of soil group classification and of its characteristic properties. The subsumption of soil unit to catena by multivariate classification of their chemical properties rather suggests similarity with the soil catena than definite pertinence. The uncertainty in classification of selected soil body pertinence to the soil catena is limitable according to using of statistically representative pit set, where is possible to obtain predominant character of common freatures. The geological environment signature uncertainty at soil catena properties relates with determination of hillwashes which cause discordances between compositions of bedrock and surface substrates especially in broken terrains (Lin, 2006). The catenas, characteristic predominantly by significant proportion of unique soil associations, were demarcated mainly in Outer Depressions, on the other hand, the catenas, characteristic by dominance of hillwashes, were demarcated in Flysch Range.

Hillwashes are the most enhanced surface substrates in Western Carpathians. Although, they are geochemically similar to bedrock, even so differences in contents of bases and P_2O_5 between the soil horizons eliminated effects of evaluated geological environment signatures on specific features of the demarcated clusters. Predominant statistically significant differences among grain size or chemical properties of the compared soil horizons correspond with presumptions about dominant hillwash proportion in OWC. The bedrock conditioned forest soil properties homogeneity in Outer Depressions and in the flat waterlogged depressions, broken nutrient-medium hillycountries and on proluvial upto submountain slopes. The differences among values of grain and chemical compositions at A- and B-horizons suggest effect of hillwashes on soil properties. The differences among grain size, BS and contents of Corg, Al_2O_3 and P_2O_5 are main features of soil heterogeneity inside the individual clusters. The most different properties of A- and B- forest soil horizons are concentrated along river systems and in the broken nutrient-poor hillycountries. The most heterogenous soil groups are concentrated on mountain slopes, but the most different P_2O_5 content occur in forest soils of the flat loess-covered hillycountries and broken nutrient-poor hillycountries. The heterogeneity of the forest soil groups in OWC is least in peneplain terrains, on massif foothills and on nutrient-medium sites, whereas the highest is on nutrient-poor sites in the broken terrains. Differences in nutrient contents among the individual clusters of highland forest soils point out hillwash fertility heterogeneity. Because soil properties diversity in OWC statistically does not correspond with altitude, the altitude transitions indicate rather terrain division from variosly resistant and fertile rocks in particular parts of Flysch Range (Pánek *et al.*, 2013). The most proportional sites flat luvic hillcountries and waterlogged depressions are predominantly presented in western and central parts of OWC, whereas the submountain and mountain slopes predominate in north-eastern parts of OWC.

CONCLUSION

Forest soils of Outer Western Carpathians are divided into catenas more conditioned by bedrock in Outer Depressions and catenas more conditioned by relief in Flysch Range. Proportion of forest soil groups and differences of properties between A- and B-horizons separate homogeneous and heterogenous catenas. The bedrock effect on soil properties is more significant in homogenous catenas, whereas the terrain effect is more significant in heterogenous catenas. Individual catenas are characteristic by base saturation, CaO and P_2O_5 content heterogeneity. The catena soil horizon properties heterogeneity is statistically more significant than soil group selected properties heterogeneity. Bedrock and terrain effects on soil properties differences among various catenas are less than differences between top-soil a subsurface diagnostic horizon properties, but the bedrock effects are moderately more significant than terrain effects.

The catenas of wetlands, river valleys, flat loess-covered and broken nutrient-medium hillycountries are concentrated in Outer Depressions. The flat loess-covered hillycountries are concentrated in southern Outer Depressions, on the contrary, the broken nutrient-medium hillycountries are concentrated on north. Flysch Range is characteristic by mountain slopes and by higher frequency of the catenas of broken hillycountries and proluvial slopes than flat hillycountries. The flat waterlogged depressions and flat luvic hillycountries are concentrated in south part of Flysch Range, whereas submountain and mountain slopes dominate in northern part.

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