ZONAL CONCEPT: LANDSCAPE LEVEL PARAMETERS AND APPLICATION

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Received: 21st May 2023, **Accepted:** 25th July 2023

ABSTRACT

Zonal concept is a traditional approach in land assessment. Although its principles have been known for over a hundred years, they have not yet been thoroughly evaluated using modern analytical approaches. Assessing the empirically established parameters for characterising a zonal site, establishing threshold values of significant environmental factors, along with assessing the applicability of the zonal concept, were the goals of this study. The data analysed were obtained from the robust and objective Czech National Forest Inventory database. Regression, indirect ordination, hierarchical clustering and spatial analyses of geo-information systems were used. The study revealed seven crucial environmental factors: Slope, Slope Height, Terrain Surface Texture, Negative Openness, Multi-Resolution Index of Valley Bottom Flatness, Soil Type and Soil Subtype. A graphical model of zonal/azonal sites was constructed based on calculated threshold values of the factors. This methodic approach introduces significant geomorphological information that are otherwise problematically detectable in field mapping. We suggest it is possible to use the zonal concept as a base layer for general landscape assessment. Zonal site classification can become a part of a precise land management practice, consisting of valuable empiricism of traditional landscape ecological classifications enriched by modelling in disturbance ecology and prediction of climate change effects.

Keywords: zonal vegetation, azonal vegetation, zonal concept, macroclimate, climax, ecological classification

INTRODUCTION

Advanced landscape assessment and survey appears as one of the most suitable ways of reflecting impact of climate change on terrestrial ecosystems (Grimm *et al*., 2013). One of the classic concepts in landscape assessment is the zonal concept (Krajina, 1965; Pojar *et al*., 1987; White, 1997; Meidinger & Pojar, 1991). This concept is deeply rooted in history and has a nonnegligible value in ecological ecosystem evaluation (Dujka & Kusbach, 2022). However, in its nearly 70 years of existence, it has experienced minor change, having remained in its empirical state (Kusbach *et al*., 2017).

The first ruminations on the zonal concept can be seen in works of V. V. Dokuchaev (1883), whose idea was based on the principle of soil zonality (Mucina, 2019). Habitat zonality concerning vegetation has later been defined by H. Walter (Mercier, 2021). Even though the habitat zonality (sensu climate-dominant influence on the presence of vegetation in a habitat) is a general ecological approach to ecosystem classification (Bailey, 2002), it has become a fundament for landscape ecological classifications development (Hills, 1952; Krajina, 1965; Zlatník, 1976; Pfister & Arno, 1980; Pojar *et al*., 1987).

A zonal site can be defined as a habitat in which vegetation evolves into a stage of the climate climax (Whitaker, 1953; Selleck, 1960). Vegetation succession is assumed here to be dependent on the influence of prevailing macroclimate (Major, 1951), while other environmental factors (terrain topography, soil or soil substrates) only play a minor role (Meidinger & Pojar, 1991). Zonal sites are characterised by these empirical parameters (Pojar *et al*., 1987): (i) medium gradient in medium slopes of mountainous (sloping) terrain (slopes with directly affected soil water regime) and upper slope positioning of platforms, (ii) position, gradient and orientation of the slope do not cause significant macroclimate modifications (do not create specifical local climate) in the form of temperature inversions, significantly isolated or shadowy locations, (iii) slight to medium slope (3–17°); in dry or cold climate, even slopes under 3°; in a wet climate up to 27°, (iv) the soil is of medium depth up to (very) deep, with more than 50 cm of massive topsoil, without any significant horizon limitations in the topsoil, with loam or sand structure of less than 50 % of skeletal fraction volume with unrestricted drainage (without the permanently conditioned presence of a groundwater table).

Landscape ecological classifications use a plethora of both vegetation and environmentally focused approaches e.g., phytosociology, geobotany (Braun-Blanquet, 1928), pedology and geology (Cajander, 1926; Pogrebnyak, 1955; Sukachev, 1944), or their combinations (Austin, 2013). These classifications have, directly or indirectly, utilised the zonal concept and its empirical, expert knowledge-based parameters. However, determination of suitable parameters that could be practically useful in site differentiation, especially when vegetation cover is changed and far from a site potential, is still absent.

The aim of this study is to (i) reveal significant parameters characterising a zonal site and (ii) assess applicability of the zonal concept through landscape ecological classifications.

MATERIAL AND METHODS

Study area

The territory of the Czech Republic (48°33–51°03‘N, 12°05‘–18°51‘E) is the study area of this work. Ecological subdivisions of the territory – the Natural Forest Areas (Plíva & Žlábek, 1986) are commonly used in forestry practice. The Natural Forest Areas (NFAs) are defined as continuous territories with similar growth conditions for a forest (Forest Act No. 289/1995). The study area is divided into 41 NFAs (Annex 1 of the 298/2018 Decree). For the data analysis, NFAs were aggregated into three spatial frames: (i) the Czech Republic: NFA (1–41); (ii) Hercynicum: NFA 1–33; (iii) Carpaticum: NFA 34–41 (Fig. 1).

Data

The analytical dataset consists of an objective data from the National Forest Inventory ground survey, second cycle (NFI II), from 2011–2015 (Kučera & Adolt, 2019). The dataset included records of 7,772 plots in total investigated on four spatial levels: s2 (2 × 2 km), s4 (4 × 4 km), s8 (8 × 8 km) and s16 (16 × 16 km). The data of spatial levels s4–s16 containing edaphic category, forest type information and the results of the soil sampling (soil type, physical and chemical properties; FMI, 2023; Viewegh *et al.*, 2003) were essential for this study. Spatial level s2 only contained information on the edaphic category, i.e., without soil information.

For the computation of morphological characteristics and humidity indexes (Table 1), a thematic raster map of the Czech Republic digital relief model, 4th generation (Anon, 2020), was used. The model represents a visualisation of natural or human-altered terrain in the digital form of discrete-points' heights inside a periodic grid (5 × 5 m) of points with the coordinates X, Y, H. The H coordinate stands for altitude in Baltic Vertical Datum - After Adjustment (Bpv), with the mean square error of the height anomaly being 0.3 m for an exposed terrain and 1 m for vegetation-covered terrain. Pixel size was adjusted to 100 × 100 m using SAGA GIS software (Conrad *et al.*, 2015).

The average annual rainfall sum and temperature for 1970–2000 were obtained from the Fick & Hijmans (2017). The climatic data pixel size was 500 × 500 m. Newer climate data of average annual temperatures and average annual rainfall was available for 1991–2014 (CHI, 2022).

For analytical purposes, the dataset has been divided into two groups based on the levels of importance: (i) GROUP_A (N = 2,076, 27 % of the dataset), plots s4–s16 (edaphic category + soil type data), (ii) GROUP_B (N = 5,696, 73 % of dataset), plots s2 (the edaphic category only). Plots with missing or incomplete data were removed. Only those plots that were in the "FORESTed" and "STAND LAND" (meaning temporarily non-forested parcel) category were chosen (Kučera & Adolt, 2019). Plots of both categories were complemented with climate and environmental data (Table 1) through geospatial analyses in the QGIS Desktop program (version 3.28.0). Data of both groups were then further divided by the edaphic categories (Dujka & Kusbach, 2022) into three groups: ZON – zonal (K, M, I, S, B, W, H, D); AZ_D – azonal, not influenced by groundwater table (X, Y, Z, J, N, F, C, A); and AZ_W – azonal, influenced by water table (L, U, V, G, T, R, O, P, Q) (Viewegh *et al*., 2003). Exposed forest types, i.e., sites with a slope gradient over 22°, were excluded from the ZON category (FMI, 2023). The Box-Cox transformation (Box & Cox, 1964) was made if the nature of the analytic method required data with normal distribution.

Fig. 1: Position, division and brief geographic characteristics of the study area. Hercynicum is defined by aggregation of Natural Forest Areas (Plíva & Žlábek, 1986) 1–33, then Carpaticum 34–41

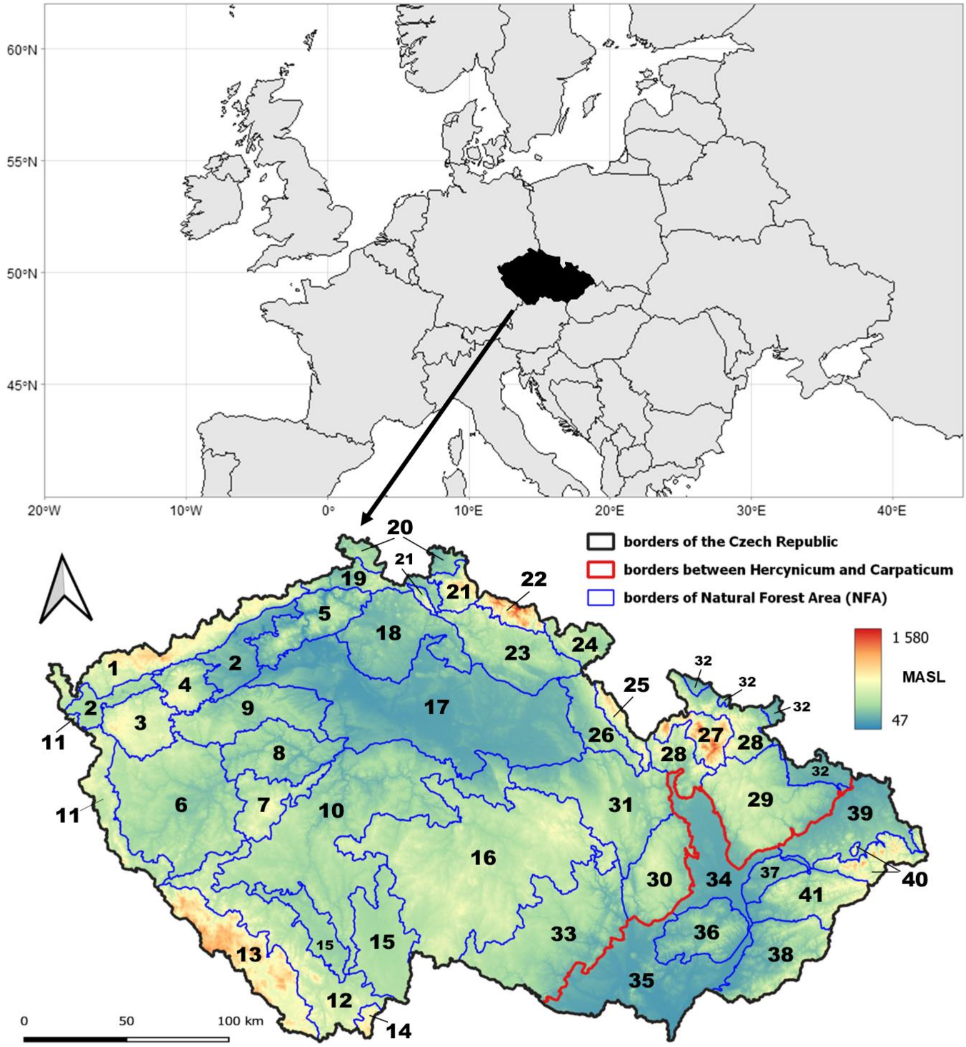


Table 1: Overview of environmental variables

Characteristics	Abbreviation	Units	Values (min–max)
Average annual temperature (1990–2014)	TEMP_ANU	°C	2.7–9.5
Average annual temperature in spring months (III–IV) (1970–2000)	TEMP_SPR	°C	1.1–10.1
Average annual temperature in summer months (VI–VIII) (1970–2000)	TEMP_SUM	°C	10.2–19.3
Average annual temperature in autumn months (IX–XI) (1970–2000)	TEMP_AUT	°C	2.7–10.2
Average annual temperature in autumn months (XI–II) (1970–2000)	TEMP_WIN	°C	-5.5–1.5
Average annual precipitation (1990–2014)	PREC_ANU	mm	472–1512
Average annual precipitation in spring months (III–IV) (1970–2000)	PREC_SPR	mm	112–312
Average annual precipitation in summer months (VI–VIII) (1970–2000)	PREC_SUM	mm	196–426
Average annual precipitation in autumn months (IX–XI) (1970–2000)	PREC_AUT	mm	94–320
Average annual precipitation in winter months (XII–II) (1970–2000)	PREC_WIN	mm	63–380
Altitude	ALT	MASL	148–1500
Slope	SLP	°	0.0–58
Aspect	ASP	°	0–360
Catchment area (Freeman, 1991)	CAT_A	km^2	400–494466
Convergence (Koethe & Lehrmeier, 1996)	CONV	%	-79–77
Convexity (Conrad *et al*., 2015)	CONX	-	0.00002–63
Diffuse Insolation (Böhner & Antonić, 2009)	DIF_INS	$kWh·m^{-2}$	1001–1308
Direct Insolation (Böhner & Antonić, 2009)	DIR_INS	$kWh·m^{-2}$	4249–7404
Total Insolation (Böhner & Antonić, 2009)	TOT_INS	$kWh·m^{-2}$	5410–8536
Gradient (Heinrich & Conrad, 2008)	GRAD	-	0.0–0.78
Multi-Resolution Ridge Top Flatness (Gallant & Dowling, 2003)	MRRTF	-	0.0–6.58
Multi-Resolution Valley Bottom Flatness (Gallant & Dowling, 2003)	MRVBF	-	0.0–7.95
Mid-slope (Böhner & Antonić, 2009)	MSLP	-	0.001–0.979
Negative Openness (Yokoyama *et al*., 2002)	NEG_O	°	1.08–1.57
Positive openness (Yokoyama *et al*., 2002)	POS_O	°	1.12–1.57
Protect Index (Yokoyama *et al*., 2002)	PROT	-	0.00–0.43
Slope Height (Böhner & Selige, 2006)	H_SLP	m	2.7–383.2
Standardised Height (Böhner & Selige, 2006)	STD_H	m	56–1456
Terrain Ruggedness Index (Riley *et al*., 1999)	T_RUG	-	0.0–13.2
Terrain Position Index (Guisan *et al*., 1999)	TPI	-	-16.0–23.5
Terrain Wetness Index (Böhner *et al*., 2001)	TWI	-	4.2–18.3
Valley Depth (Conrad *et al*., 2015)	VAL_D	m	1.8–285.6
Terrain Surface Texture (Iwahashi & Pike, 2007)	TEX	-	0–100
Soil substrate	SUBSTRAT	-	Category
Soil type	SOIL_TYP	-	Category
Soil subtype	S_SUBTYP	-	Category

Methods

Multidimensional statistical analyses were chosen for analytical evaluation. Analyses were carried out in the software R-Studio (version R.4.1.2, RStudio Team, 2020).

Random Forest

Analysis using the Random Forest (RF) method was used to reduce the huge number of input environmental variables so that the most significant factors are revealed.

For analysis by the RF classification method (Breiman, 2001; Klashka & Kotrč, 2004), we used GROUP_A under the supervision of the categories ZON, AZ_D and AZ_W. The package “randomForest” (Liaw & Wiener, 2002) in the R-studio has been used. The algorithm arranged the significant factors in the importance analysis according to Mean Decrease Accuracy (MDA) and Mean Decrease Gini (MDG). For the training process of the RF model, the number of RF trees *ntree* = 500; 1,000; 1,500 were used, and the number of variables randomly employed in every tree composition *mtry* was calculated using the R command *bestmtry*. The resulting RF model was verified by comparing the model accuracy (*Accuracy*) with *No information* rate values and further with the kappa index value (Landis & Koch, 1977). For further analysis, we used those 10 environmental variables which were found to be the most important in the RF analysis.

Principal Component Analysis

Principal Component Analysis (PCA) was used to reveal mutual relations between the most important 10 environmental variables obtained by the RF analysis. A matrix chart was created for GROUP_A using the R command corrplot and only those variables with a lower mutual correlation than 0.75 according to the Pearson correlation coefficient were chosen. The correlation matrix with seven least correlated variables was centralized and standardized. The package “factoextra” (Kassambra & Mundt, 2020) and “vegan” package (Oksanen *et al*., 2022) was employed. For interpreting significant principal components (PC), we used (i) the Kaiser criterion: eigenvalues > 1 (Kaiser, 1960); and (ii) graphic interpretation using Cattel’s scree plot (Meloun & Militký, 2012). The PCA results were graphically interpreted with the use of a biplot, the Pearson correlation coefficient was calculated after verifying the relation between the significant components and the input variables (“envfit” function). In addition, we have discovered the rate of each variable’s contribution to the variability of a given component (“get_pca_var” function). The Kaiser criterion was used to determine primarily the two most significant components – PC1 and PC2.

Classification and Regression Trees

For the analysis with the Classification and Regression Trees method (CART; Breiman *et al*., 1984), the more robust dataset GROUP_B was used with variables whose importance was revealed in RF and verified by PCA. The data were normalised using the Box-Cox transformation (Meloun & Militký, 2012). The “rpart” package (Therneau *et al.*, 2013) was used for the analysis. For the model, we set the following input parameters: the minimum number of observations as 10 (function parameter *minsplit*); and the minimum number of observations in the terminal junction as 5 (function parameter *minbucket*). The classification tree was tested through cross-validation of the R command *xval*, the complexity parameter value *cp* was also specified for the model correction. The corrected model was simplified using the R command *prune* (Komprdová, 2012). The obtained transformed threshold values were then retransformed into the original data units.

The threshold values were experimentally calculated for the spatial frames the Czech Republic, Hercynicum and Carpaticum. The match of the represented values was verified for the most significant variables of the NFI II dataset among the spatial frames with non-parametric MANOVA (Multivariate Kruskal-Wallis test; Katz & McSweeney, 1980) with the level of significance p = 0.05. In case of statistically significant difference between the calculated tree branches, this difference was verified by the multiple p-values comparison method (Steel, 1960). The STATISTICA 12.0 software was used.

Geospatial analyses and modelations

The CART threshold values were employed in creating classification intervals for the spatial frames the Czech Republic, Hercynicum and Carpaticum. Using the raster calculator in the QGIS (2022) Desktop interface (version 3.28.0), classification intervals were displayed in thematic raster maps and transferred into vector geometry. Each classification interval represented one numbered polygon. All such polygons, made for significant factors, were mutually intersected. Each intersection (new polygon) was assigned a unique identificator, the ID consisting of digits of the intersecting intervals. Using the *Zonal statistics* tool, mean values of the original factors were calculated. The vector layer with a table of attributes titled CLUSTER produced in such a manner became the foundation for cluster analysis.

Cluster analysis

The cluster analysis aimed to reduce the number of the subsequent CLUSTER polygons into several unique geographical structures. In the R interface, the cluster analysis was made using the “stats” package (R Core Team, 2013) and the Distance Matrix Computation (*dist*) command, with the Euclidean metric command *euclidean* (geometric distance). Further, using the *map_dbl* function, the most proper clustering method for agglomerative hierarchic clustering (i.e., for calculating the distance between two clusters) was chosen. The analysis assigned a cluster number for each polygon of the CLUSTER vector layer, and polygons of the same number were merged. In this way, we created a new polygon layer named CLUSTER_REDUC. The uniqueness of the polygons joined in the CLUSTER_REDUC layer was tested using the multidimensional dispersion analysis (MANOVA) with p = 0.05. For the testing, one thousand random points were generated for each polygon of this layer with values of factors whose significance was discovered by the RF analysis and verified by PCA. The statistical significance of the CLUSTER_REDUC polygon layer was verified using the Pillai’s Trace test (Howit & Cramer, 2014). Finally, the polygon layers CLUSTER_REDUC were described and interpreted in a thematic cartogram.

RESULTS

Random Forest

The RF classification revealed a classification error of 16.7 % (ntree = 500 – 1000, the best of the mtry values found = 7). The ideal percentage of correctly classified values according to the confusion matrix was found in the ZON category (93 %) and AZ_W (75 %), while the AZ_D category had the highest error rate (55 %). The model’s accuracy (Accuracy) reached 84.5 % (with reliability interval between 80.9 and 87.7 %), and the No information rate index went up to 60.0 %. The Kappa index value was 0.69. The variables’ importance was very similar based on the randomisation method (Mean Decrease Accuracy, MDA) and Gini index (Mean Decrease Gini, MDG). According to MDA and MDG, the best scores for the first ten variables were reported (Table 2).

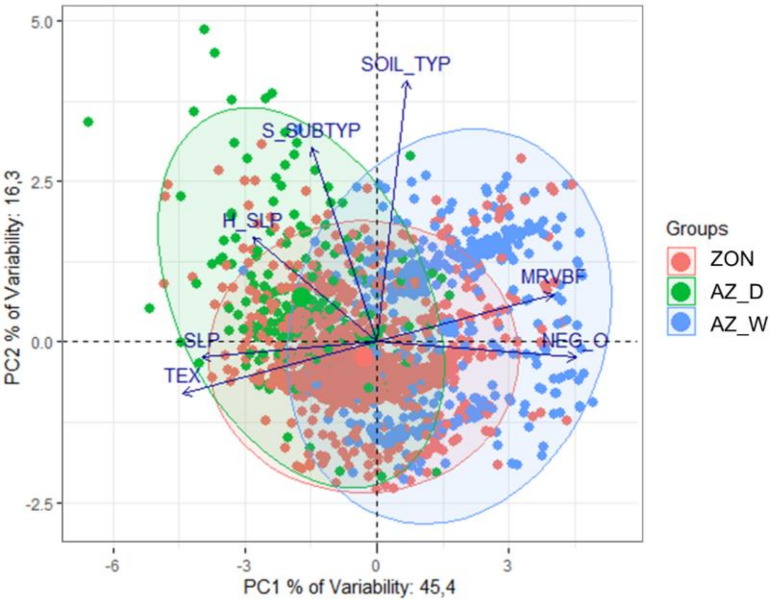
Table 2: Variable importance based on the randomization method (MDA) and Gini index (MDG) for the 10 most important variables

Variable	Mean Decrease Accuracy (MDA)	Mean Decrease Gini (MDG)
SOIL_TYP	57.72	77.23
S_SUBTYP	49.03	51.74
NEG_O	28.02	28.61
SLP	26.47	23.94
MRVBF	25.55	24.55
CONX	24.56	20.60
TEX	23.26	20.08
H_SLP	23.12	16.04
T_RUG	21.87	20.97
SUBSTRAT	21.03	8.02

Principal Component Analysis

Indirect PCA ordination revealed the first (PC1) and second (PC2) principal components as the most important for interpreting variables' mutual relations. Cumulatively, the first two components explain 61.7 % (Fig. 2).

Fig. 2: Biplot of the mutual position of factors with regards to the first (PC1) and the second (PC2) principal component. See Table 1 for abbreviations



The PC1 was interpreted as a "geomorphological environmental gradient". The gradient consists of five input factors: Negative Openness (NEG_O), which contributes to the variability with 24.8 % and correlates positively with PC1 (r = 0.99); Terrain Surface Texture (TEX), contributing with 23.5 % to the variability and negatively correlating with PC1 (r = -0.95); Multi-Resolution Valley Bottom Flatness (MRVBF) contributing with 19.7 %

variability and positively correlating with PC1 (r = 0.95); Slope (SLP) contributes with 20.2 % and negatively correlates with PC1 (r = -0.99). The Slope Height factor (H_SLP) has a slightly lower correlation rate with PC1 (r = -0.72), contributing with 9.7 % of the total variability.

The PC2 was interpreted as a “pedogenetic gradient” and is made of mutually positively correlated factors SOIL_TYP (soil type) and S_SUBTYP (soil subtype). Soil type contributes with 55.7 % to the overall variability and positively correlates with PC2 (r = 0.99), soil subtype contributes with 31.0 % and positively correlates with PC2 (r = 0.95). Positive correlation points to the prevalence of soil-forming processes.

Classification and Regression Trees

The results of the RF and PCA analyses established a total of seven statistically significant factors, out of which five were suitable for CART (excluding the SOIL_TYP and S_SUBTYP categorical variables, as the analytical GROUP_B did not contain these data): SLP, TEX, NEG_O, H_SLP and MRVBF (Table 3).

Table 3: CART results: the mean ($\bar{x}$), minimum (min.) and maximum (max.) values of the spatial frame variables

Variable	Hercynicum			Carpaticum			Czech Republic		
	min.	$\bar{x}$	max.	min.	$\bar{x}$	max.	min.	$\bar{x}$	max.
SLP	2.48	6.36	15.40	3.41	9.09	18.23	2.52	6.70	15.41
TEX	37.33	46.64	49.13	34.62	53.16	55.99	36.38	47.45	50.43
NEG_O	81.48	86.38	87.54	80.15	83.68	87.59	81.38	84.78	87.57
H_SLP	18.50	32.52	53.60	11.95	37.17	77.99	17.26	33.11	58.60
MRVBF	0.0009	0.12	1.09	0.00002	0.024	0.54	0.0007	0.10	1.02

The null hypothesis of the variables‘ conformity (Table 3) for the spatial frames the Czech Republic, Hercynicum and Carpaticum has been rejected by the Multivariate Kruskal-Wallis test. For the SLP variable, the result was H(2) = 101.23, p = 0.00; for TEX: H(2) = 190.97, p = 0.00; for NEG_O: H(2) = 67.23, p = 0.00; for H_SLP: H(2) = 10.57, p = 0.01; for MRVBF: H(2) = 76.60, p = 0.00). Multiple comparisons of p-values revealed statistically significant differences among all spatial frames in the SLP, TEX and MRVBF variables. In the case of the NEG_O and H_SLP variables, no statistically significant difference was found between the Hercynicum and the Czech Republic frames; both were nevertheless found to be significantly different to Carpaticum.

Classification value intervals of the spatial frames‘ factors are listed in Table 4. The ‘No.‘ column represents the number of classification intervals arranged in ascending order (the lowest number equals the lowest interval values). By mutual intersection of the classification intervals, the number of (i) 1,092 polygons was created for Hercynicum, (ii) Carpaticum = 517 polygons, and (iii) the Czech Republic = 701 polygons. Each polygon used in the next cluster analysis was labelled with an ID of a five digit code, consisting of the digits in the ‘No.‘ column; e.g., the first polygon was given the ID 11111, the second 11112, and so on.

Table 4: Intervals of each factor's values for the Czech Republic, Hercynicum and Carpaticum spatial frames

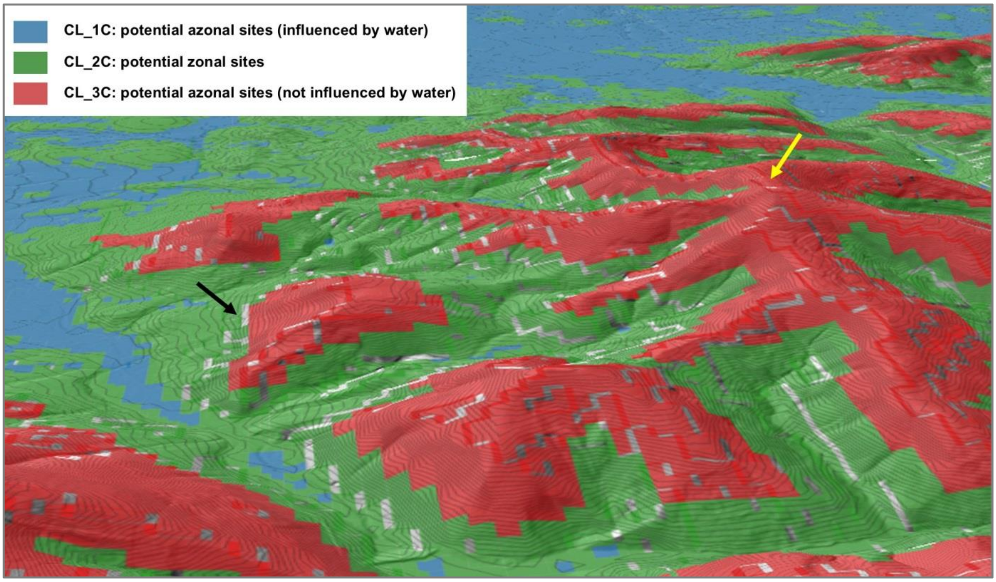
Factor	No.	Hercynicum	Carpaticum	Czech Republic
SLP (°)	1	< 2.48	< 3.41	< 2.52
	2	2.48–5.86	3.41–7.92	2.52–6.07
	3	5.86–9.73	7.92–12.77	6.07–10.05
	4	9.73–15.40	12.77–18.23	10.05–15.41
	5	15.40 >	18.23 >	15.41 >
TEX	1	< 37.33	< 34.62	< 36.38
	2	37.33–45.99	34.62–48.37	36.68–45.15
	3	45.99–49.13	48.37–54.72	45.15–48.77
	4	49.13 >	54.72–55.99	48.77–50.43
	5		55.99 >	50.43 >
NEG_O (°)	1	< 81.48	< 80.15	< 81.38
	2	81.48–84.08	80.15–82.94	81.38–84.01
	3	84.08–85.81	82.94–85.31	84.01–85.80
	4	85.81–87.54	85.31–87.59	85.80–87.57
	5	87.54 >	87.59 >	87.57 >
H_SLP (m)	1	< 18.50	< 11.95	< 17.26
	2	18.50–28.59	11.95–25.86	17.26–28.19
	3	28.59–38.74	28.86–43.00	28.19–40.04
	4	38.74–53.60	43.00–77.99	40.04–58.60
	5	53.60 >	77.99 >	58.60 >
MRVBF	1	< 0.0009	< 0.00002	< 0.0007
	2	0.0009–0.05	0.00001–0.003	0.0007–0.04
	3	0.05–0.27	0.003–0.02	0.04–0.22
	4	0.27–1.09	0.02–0.54	0.22–1.02
	5	1.09 >	0.54 >	1.02 >

Cluster analysis

Cluster analysis performed for each spatial frame determined the optimal number of 3 clusters for Hercynicum (CL_1H, CL_2H, CL_3H), Carpaticum (CL_1C, CL_2C, CL_3C) and the Czech Republic (CL_1CR, CL_2CR, CL_3CR). The null hypothesis of a match was rejected, and the differences between the clusters were found to be statistically significant (Pillai test = 1.00; F(5; 20,982) = 9,177,533; $p < 0.05$). The Tukey's HSD post hoc test results are summarised in Appendix 4 The most similar clusters were found between the Hercynicum and the Czech Republic spatial frames (CL_1H and CL_1CR, CL_2H and CL_2CR), where the null hypothesis was not rejected for 3, or rather 4 factors. The null hypothesis has also not been rejected for 2 factors when comparing Carpaticum and the Czech Republic (CL_1C and CL_1CR, CL_2C and CL_2CR). The difference between spatial clusters Hercynicum and Carpaticum appeared statistically the most significant. We produced a graphic output of the cluster analysis for the Carpaticum spatial frame (Fig. 3).

Fig. 3: Cartogram of the cluster analysis results of the Carpaticum spatial frame. Gray isolines represent contour lines 10 m apart

The yellow arrow points to the highest peak of Moravian-Silesian Beskids (Lysá hora, 1,324 meters above sea level), black arrow points to a disagreement (noise) of layers in the geospatial analysis.



DISCUSSION

The zonality of a site can be characterised with the help of geomorphologic and pedogenetic gradient interpretation. The geomorphologic gradient can be assessed using geoinformation analyses of significant environmental variables. This gradient differentiates between macroclimate (general climate altitudinally dependent) and mesoclimate (local climate dependent on a local topography) (Major, 1951). The pedogenetic gradient, on the other hand, renders the "hidden" properties of a site such as a long-term soil evolution via a prevailing pedogenetic process and related soil properties (Vavříček & Kučera, 2017; Šimek *et al.*, 2019).

Analytical approach to assessing zonality

For zonal sites' assessment, significant environmental factors (SLP, TEX, NEG_O, H_SLP, MRVBF, SOIL_TYP and S_SUBTYP), along with statistically significant differences of values between them for three spatial frames (the Czech Republic, Hercynicum and Carpaticum), were revealed. While the Carpaticum spatial frame varied from both Hercynicum and the Czech Republic in all factors, differences between Hercynicum and the Czech Republic were limited to only three factors. As we see it, utilising two frames (Hercynicum and Carpaticum) instead of just one (the Czech Republic) seems more preferable in environmental characterisation, as the Czech Republic frame lacks precision, namely in the description of the eastern parts of our study area. For this reason, we specifically listed the characteristics of Hercynicum (Appendix 3) and Carpaticum zonal sites only (Appendix 2). Differences stemmed primarily from the diverse geological (Moores

& Fairbridge, 1997; Chlupáč, 2011) and geomorphological essences of both spatial frames (Bína & Demek, 2010; Pánek & Kapustová, 2016) that also necessarily reflect different fertility (nutrient) and moisture regimes in forest soils (Hedrich, 2018).

As opposed to similar studies, e.g., Kusbach *et al.* (2019), we used a somewhat coarse resolution of the digital relief model for the environmental analyses, as choosing a more precise grid could possibly lead to skewed results with noise at the spatial scale of the Czech Republic. For example, Deng *et al.* (2007) pointed to the decrease in values of the Pearson correlation coefficient in relation to the increase in pixel size; however, that is also dependant on the respective factor's sensitivity. On the other hand, Trnka *et al.* (2020) used coarse grid resolution (500 × 500 m) for drought assessment of the Czech Republic because of large spatial variability of soil condition. Ďuričiová & Pružinec (2022) remarked on the differences in diffuse insolation error rates in mountainous terrains in varying grid sizes. The dissimilarities were not so significant in flat terrains. Volařík (2010) used fine grid resolution of the digital elevation model (5 × 5 m and 10 × 10 m) for modelling of altitudinal vegetation zones in Carpathian region in study area of 100 km^2. The coarser digital relief model resolution used in our study could produce different results compared with a more refined grid (e.g., LiDAR digital terrain model with 10 m resolution). In the next step, it would be desirable to verify environmental factors' sensitivity towards grid size for the specific area in regional (10–200 km) and local (1–10 m) scales (Pearson & Dawson, 2003) for both spatial frames. The selected resolution should then be the compromise between the technical capabilities of processing large data files and the details of the model presented.

We appeal to emphasize the practical usage of the significant environmental factors. Usage of the factors (except for SLP, SOIL_TYP and S_SUBTYP) appears very complicated to grasp practically in the field. Seeking for proper alternatives is needed (for practical use in the field, see Appendix 1). Limitation of the practical usage of some "technical" factors is obvious from the following factors‘ characteristics.

Slope (in °) traditionally belongs among the most commonly used and readily measured site parameters (Pitko & Plíva, 1967; Kučera & Adolt, 2019). In literature, a zonal site is described as a site with mild (3–7°) to medium (7–2°) slope gradient (Novotný *et al.*, 2013); mild (2–5°) to considerably steep (5–15°) slopes (Demek, 1987); and in the Jahn *et al.*, (2006) classification, the gradient of a zonal site corresponds with a very mild (3–6°), mild (6–8.5°) and, partially, even inclined slopes (8.5–15°). Zlatník (1975), on the other hand, categorised a mild slope by up to 10° and a medium slope to 20°. The criteria of a mild to medium slope, listed in the Biogeoclimatic Ecosystem Classification, BEC (Pojar *et al.*, 1987; Meidinger & Pojar, 1991), came the closest to our results. In combination with slope length, the gradient is connected to prevailing pedogenetic processes (Barbosa *et al.*, 2015; Fazlollahi Mohammadi *et al.*, 2016; Vavříček & Kučera, 2017), including their impact on the speed and quality of a mineral nutrients‘ distribution and organic matter decomposition in the humus layer (Hu *et al.*, 2021). The slope gradient is also a nonnegligible part of evaluation when it comes to assessment of technical-economic limitations of both forestry (Vavříček *et al.*, 2014; Lundbäck *et al.*, 2021) and agricultural (Jahn *et al.*, 2006; Novotný *et al.*, 2013) practices.

Slope Height (in m) belongs among the significant parameters characterising mainly landscape features of anthropogenic origin, such as stone quarries (Karaman, 2019; Shiferaw, 2021). Slope height can be used as an input parameter for the slope length calculation, a factor far more easily verified in practice. Slope height of zonal sites moves between 35–60 m in the Carpaticum spatial frame; a model case with a 10° slope gradient corresponds with a 201–345 m slope length. These can be interpreted as slopes of medium length. For azonal sites influenced by groundwater table, slope length ranges in lower values

(86–104 m) as opposed to much higher values of azonal dry site slopes (495–772 m). The values in the Hercynicum spatial frame are generally lower – zonal sites‘ slope length ranges between 86 and 260 m. Similar results are stated by, e.g. Panagos *et al.* (2015) in their calculations of the LS factor (slope length and gradient factor). With increasing values of slope height, slope instability also increases, as well as the risk of a landslide (Çellek, 2020), which deems azonal sites more prone to such events (Qui *et al.*, 2017). On lengthy slopes, faster drainage may also occur, increasing the risk of erosion (Lal, 1988). These factors can, in total, influence a hydric soil regime and soil components‘ dislocation or erosion, resulting in a change of a zonal to azonal site (Walter & Breckle, 2009).

Terrain Surface Texture (Iwahashi & Pike, 2007) can be defined as a measure of structurally spatial variability of the terrain (Trevisani *et al.*, 2012). Although the unit scale is very similar to percentages, it is not desirable to use percentages as a unit of measurement in TEX (Iwahashi & Pike, 2007). The calculations are made by the division of “peaks” and “pits”, indicating the outlay of valleys and peaks (Iwahashi *et al.*, 2001). Zonal sites can be described as sites with moderately favourable terrain texture at a broader scale (min. 1 km^2), with the portion of “peaks” and “pits” inside the interval of 40–55. Values for azonal sites influenced by the groundwater table are much lower (10–40), while for azonal “dry” sites not influenced by water, the values are comparable with zonal sites (45–57). More favourable are the Hercynicum spatial frame values; Carpaticum was proven to show higher values. That is given by easily eroded clayee-sandstone rock components of the Carpathian Flysch Belt (Plašienka *et al.*, 1997). The medium value of terrain variability (TEX) corresponds with the BEC classification criteria for a zonal site (Pojar *et al.*, 1987), i.e., it does not cause significant macroclimate modifications (does not create specifical local climate). Higher texture variability could result in the evolution of specific meso- or microclimate. With sites of terrain texture above 60, naturally azonal sites can be expected.

Negative Openness (Yokoyama *et al.*, 2002; Doneus, 2013) determines the “shutness” of a landscape. Its sense stems from a prevalent landscape matrix –various sizes of catchments consisting of valleys and ridges. Planar terrain shapes (values close to 90°) or concave ones (the lower the value, the higher the occurrence of convex terrain shapes) are prevalent. Zonal sites can be characterised as sites with prevalent concave terrain features, defined by values ranging from 80° to 88°. Azonal, water-influenced sites‘ values are 88–89°, representing both broad basins of big rivers (flat surfaces) and planar terrain shapes of smaller water courses with predominant sedimentation processes. On the contrary, dry azonal sites reach 74°–85° values – this signifies a transition between concave and convex shapes in terrain configuration. In this dry azonal site category, overall values are lower than 80°. These sites would also encompass convex terrain shapes, meaning mostly ridges and mountain ranges, where climate differences are expected.

Multi-Resolution Index of Valley Bottom Flatness (Gallant & Dowling, 2003) identifies areas with alluvial/colluvial sediments. Values close to zero correspond with low sedimentation levels (and the prevalence of other soil-forming processes); high values indicate a more intense sedimentary process caused by water and gravity. Zonal sites can be defined as those where other than sedimentary processes are prevalent or where neither erosion nor sedimentation is significantly expressive. In the analysis, index values of Carpaticum and Hercynicum are more or less similar, with mean values of 0.4 (Carpaticum) or 0.5 (Hercynicum). Mean values are however noticeably higher (4.9 or 3.5) in azonal, water-influenced sites where sedimentation, driftwood material accumulation and long-term effect of water can be expected. On the other hand, the values of dry azonal sites (being more conditioned by erosion and normal hydric regime) stood much lower (0.03 or 0.1). De Oliviera Junior *et al.* (2022) used MRVBF to analyse hydropedologic processes in the

Lontara river catchment area (Brazil). Their study's results point to the presence of gleysols in sites where MRVBF > 2, whereas sites with MRVBF values < 0.5 represented eroding surfaces with the occurrence of regosol. Van Dijk et al. (2007) used MRVBF as a suitable geospatial tool for slope and alluvium classification in the Goulburn Broken catchment area (Australia).

A partially correlated connection between the NEG_O and MRVBF (Gallant & Dowling, 2003), derived from the PCA analysis results, points out to mutually conditioned relation between the slope shape and extent of erosion or sedimentation. While concave terrain shapes do condition accumulation-sedimentary processes, erosion prevales over sedimentation in convex shapes. Likewise, the relation between sedimentation and sloping can be made. In slopes with higher gradient (generally more texturally differentiated), erosion is prevalent over sedimentation and vice versa.

Improved definition of zonality

The submitted definition originates from the analysis of the geomorphological gradient factors. Zonal sites can be defined as (i) sites with mild to medium slope gradient falling into the range of 3–15°; (ii) slopes of medium length with a prevalent concave shape, sites found in mid positions of slopes with a long-term lack of material transport and accumulation due to sedimentary processes (fluviation, alluviation, colluviation), and a lack of erosion; (iii) sites with a favourable structure of the terrain surface, i.e., the variability (proportion) of terrain elevations and depressions in wider surroundings only stands up to 60 %. For sites defined as such, there is a lower risk of occurrence of specific meso- or microclimate that would affect a character of potential vegetation; (iv) soils of a normal hydric regime with no groundwater table.

The definition of zonality needs to be specified further using the information about soil type and subtype (pedogenetic gradient). Additionally, the definition does not consider soils with intermittent water content (Stagnosols) or soils with a high percentage of a rock fragment content (over 50 % by volume), i.e., namely the Regosol and Leptosol reference class (Němeček et al., 2011). In the meantime, sites not supported by the definition of zonality need to be classified as the azonal sites.

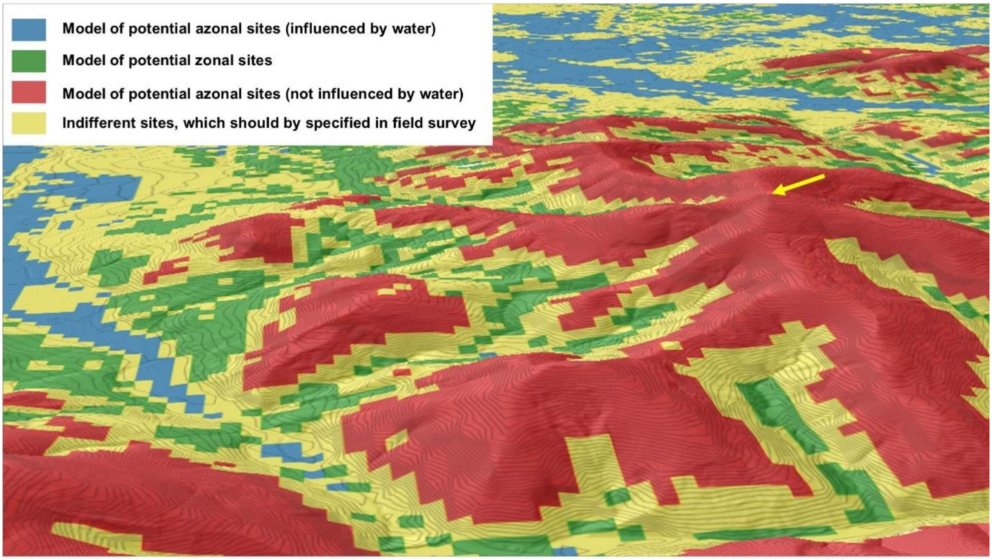
The zonal concept and its practical application

Zonal sites could be mapped using the zonal concept with a three-step process: (i) preparation of a documentation as GIS outputs. This preparation should consist of creating a model of zonal sites based on significant factors’ threshold values (Table 5). These values can be used for calculations of such graphic model (Fig. 4). With the use of threshold values, it is possible to model the occurrence of azonal sites in a similar manner as well. Limited soil data might be the weakness of such model, so this output accounts for a visualisation of a geomorphological gradient diminishing the disadvantage. While potential water-influenced azonal sites are, in many cases, easier to detect through sampling, potential dry azonal sites do share some factor similarities (mostly TEX, partly SLP). This is, to a large extent, caused by the input data complicating the calculation and modelation (slope incline appears as the most problematic, because in the original dataset, forest types mapped as non-exposed showed up in zonal edaphic categories, but their gradient exceeded the limit of 22° even by 10° in some cases). The terrain surface texture factor also cannot unequivocally determine the zonality of a site. Nevertheless, these shortcomings are solvable in the step (ii) by verifying the zonality of a site via a field survey and specifying zonality borders between zonal and azonal sites. This step should include site surveying along with a simple verification of edaphic characteristics (e.g., a soil probe or a test pit); uneasily accessible sites could be inspected via an unmanned aerial vehicle (UAV, e.g., a drone) (Rusnák *et al*., 2018). The borders of an azonal water-influenced site could be inspected using thermovision (Zhang & Zhou, 2016). Verified borders are to be recorded on a map using the GPS, the map having a thematic layer with the calculated model. The utilisation of a phytoindication is also a crucial step, mostly in hydrophilous and xerophilous communities. In the last (iii) step, terrain findings are evaluated, and sites' zonality borders are specified on a map. This thematic map (see the difference between Fig. 3 and 4) is the final output, employable, for instance, in vertical environmental differentiation of a site supported by appearance of potential (close to natural) vegetation (e.g., Viewegh *et al*., 2003; Kusbach *et al*., 2017).

Table 5: Zonal site parameters for conducting a model (Carpaticum and Hercynicum)

Factor	Carpaticum			Hercynicum		
	min.	$\bar{x}$	**max.**	**min.**	$\bar{x}$	**max.**
Slope (°)	3.0	9.0	15.0	2.0	7.0	12.0
Terrain Surface Texture	30	45	60	30	42	55
Negative Openness (°)	80	84	88	84	86	88
Slope Height (m)	35	47	60	15	30	45
Multi-Resolution Valley Bottom Index	0.0005	0.4	0.9	0.01	0.5	0.9

Fig. 4: Graphical model of zonal/azonal sites in Moravian-Silesian Beskids
The parameters for modelling zonal sites (in green): Slope 3–15°, Terrain Surface Texture 30–60, Negative Openness 80–88°, Slope height 35–60 m, Multi-Resolution Valley Bottom Index 0.0005–0.9. Azonal "wet" sites (in blue) have lower values than the bottom threshold of the value ranges. On the other hand, "dry" azonal sites (in red) surpass the upper threshold values of zonal parameters. Indifferent sites are difficult to categorise, as either (a) their parameters are not complementary in all five aspects; (b) the intervals would overlap in reality; (c) they form the threshold values between the zonal/azonal sites and need to be calibrated by filed surveying. Grey isolines represent contour lines 10 m apart. The yellow arrow points to the highest peak of the Moravian-Silesian Beskids (Lysá hora, 1,324 meters above sea level).



The application of the zonal concept is a suitable tool for ecological assessment of a land, including forests. The possibility of modelling a zonal site using geoinformation analyses along with mathematically statistical methods, which can be a theoretical blueprint for terrain survey, is advantageous. The zonality principle filters out the effect of altitudinal (macro) climate, putting more emphasis on its morphological essence of a site, i.e., the effect of topo/mesoclimate. This allows for describing and distinguishing a zonal site regardless of altitude or a geographic location. This can be found efficient in recent efforts of modelling of the unstable global environment and its relevant reflections in vegetation, i.e., potential migration (Williams & Dumroese, 2013; Gömöry *et al.*, 2020).

CONCLUSION

In this study, we used a robust regional dataset and advanced the concept of zonality, using scientifically assessed environmental parameters. Seven significant factors were established that could be practically used to better characterize and map a zonal site. There are two types of factors, characterized by their relation to climate: (i) factors indirectly dependent on climate (Slope, Slope Height, Terrain Surface Texture, Negative Openness and Multi-Resolution Index of Valley Bottom Flatness); (ii) factors indirectly conditioned by climate are more affected by geological processes (weathering, erosion) or pedogenetic processes (including soil type and soil subtype, both commonly investigated in practice).

The study reveals environmental differences between the spatial frames in the study area; the Hercynian and Carpathian systems. Nevertheless, zonal sites in these spatial frames can be characterized and mapped by threshold values of identical, climatically indirectly dependent factors.

The zonal concept is a suitable and perspective approach to forest site assessment as well. Precisely processed outputs, combining virtual modelation and field research, can become valuable e.g., for vertical forest vegetation zonation improvement and prediction of potential migration of vegetation. In combination with geobotanical approach, zonal site classification can become a part of a precise land management practice, consisting of valuable empiricism of traditional landscape ecological classifications enriched by modeling in disturbance ecology and prediction of climate change effects.

ACKNOWLEDGEMENTS

This research was curated as a subunit part of a dissertation thesis (‘Evaluation of Superstructural Units of the Czech Forest Ecosystem Classification based on the National Forest Inventory Data‘) on the grounds legally provided data of the National Forest Inventory, Forest Management Institute, Brandýs nad Labem, contract no. 20200010-ISAT.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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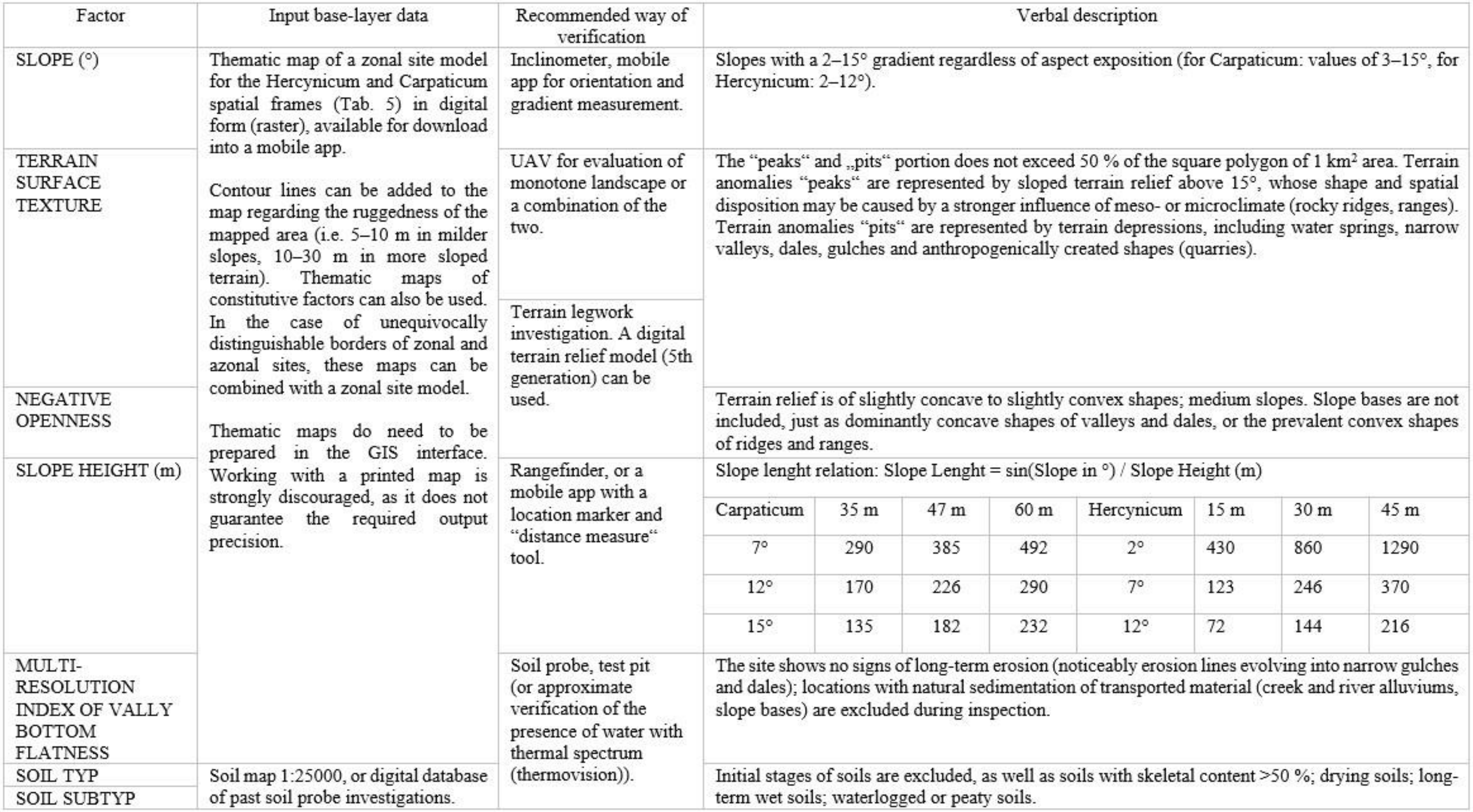
APPENDIX

Appendix 1: Suggestion of criteria for zonality assessment with the use of significant environmental factors (incl. SOIL_TYP and SOIL_SUBTYP)



<table>
<tr><th>Factor</th><th>Input base-layer data</th><th>Recommended way of verification</th><th colspan="8">Verbal description</th></tr>
<tr><td>SLOPE (°)</td><td rowspan="10">Thematic map of a zonal site model for the Hercynicum and Carpaticum spatial frames (Tab. 5) in digital form (raster), available for download into a mobile app.
Contour lines can be added to the map regarding the ruggedness of the mapped area (i.e. 5–10 m in milder slopes, 10–30 m in more sloped terrain). Thematic maps of constitutive factors can also be used. In the case of unequivocally distinguishable borders of zonal and azonal sites, these maps can be combined with a zonal site model.
Thematic maps do need to be prepared in the GIS interface. Working with a printed map is strongly discouraged, as it does not guarantee the required output precision.</td><td>Inclinometer, mobile app for orientation and gradient measurement.</td><td colspan="8">Slopes with a 2–15° gradient regardless of aspect exposition (for Carpaticum: values of 3–15°, for Hercynicum: 2–12°).</td></tr>
<tr><td rowspan="2">TERRAIN SURFACE TEXTURE</td><td>UAV for evaluation of monotone landscape or a combination of the two.</td><td colspan="8" rowspan="2">The “peaks“ and „pits“ portion does not exceed 50 % of the square polygon of 1 km² area. Terrain anomalies “peaks“ are represented by sloped terrain relief above 15°, whose shape and spatial disposition may be caused by a stronger influence of meso- or microclimate (rocky ridges, ranges). Terrain anomalies “pits“ are represented by terrain depressions, including water springs, narrow valleys, dales, gulches and anthropogenically created shapes (quarries).</td></tr>
<tr><td rowspan="2">Terrain legwork investigation. A digital terrain relief model (5th generation) can be used.</td></tr>
<tr><td>NEGATIVE OPENNESS</td><td colspan="8">Terrain relief is of slightly concave to slightly convex shapes; medium slopes. Slope bases are not included, just as dominantly concave shapes of valleys and dales, or the prevalent convex shapes of ridges and ranges.</td></tr>
<tr><td rowspan="5">SLOPE HEIGHT (m)</td><td rowspan="5">Rangefinder, or a mobile app with a location marker and “distance measure“ tool.</td><td colspan="8">Slope lenght relation: Slope Lenght = sin(Slope in °) / Slope Height (m)</td></tr>
<tr><td>Carpaticum</td><td>35 m</td><td>47 m</td><td>60 m</td><td>Hercynicum</td><td>15 m</td><td>30 m</td><td>45 m</td></tr>
<tr><td>7°</td><td>290</td><td>385</td><td>492</td><td>2°</td><td>430</td><td>860</td><td>1290</td></tr>
<tr><td>12°</td><td>170</td><td>226</td><td>290</td><td>7°</td><td>123</td><td>246</td><td>370</td></tr>
<tr><td>15°</td><td>135</td><td>182</td><td>232</td><td>12°</td><td>72</td><td>144</td><td>216</td></tr>
<tr><td>MULTI-RESOLUTION INDEX OF VALLY BOTTOM FLATNESS</td><td rowspan="3">Soil probe, test pit (or approximate verification of the presence of water with thermal spectrum (thermovision)).</td><td colspan="8">The site shows no signs of long-term erosion (noticeably erosion lines evolving into narrow gulches and dales); locations with natural sedimentation of transported material (creek and river alluviums, slope bases) are excluded during inspection.</td></tr>
<tr><td>SOIL TYP</td><td rowspan="2">Soil map 1:25000, or digital database of past soil probe investigations.</td><td colspan="8" rowspan="2">Initial stages of soils are excluded, as well as soils with skeletal content >50 %; drying soils; long-term wet soils; waterlogged or peaty soils.</td></tr>
<tr><td>SOIL SUBTYP</td></tr>
</table>

Appendix 2: The name and characteristic of clusters for the Carpaticum spatial frame (the interval of values represents the lower (25 %) and upper (75 %) quartile of 1,000 randomly generated points)

Cluster	Name	Description based on significant factors
CL_1C	Potentially zonal	Mild to medium inclined slopes (4.6–10.7°) with favourable to moderately favourable terrain texture (the portion of evenly shaped terrain and terrain relief abnormalities in 1 km^2 area falls into the interval of 40–55). The slopes are mildly concave (NEG_O: 83.7–87.1). Slope height ranges between 20–43 m. From the perspective of pedogenetic processes, erosion is prevalent over sedimentation, or both processes are evenly present (MRVBF: 0.02–0.51).
CL_2C	Potentially azonal – influenced by groundwater	Flat surfaces (0.6–2.3°) up to 3° slope gradient with very favourable terrain texture (the portion of evenly shaped terrain and terrain relief abnormalities in 1 km^2 area is low, 13–30) with a prevalence of flat terrain shapes (NEG_O: 88.6–89.7°). Slope height ranges between 11–17 m. From the perspective of pedogenetic processes, sedimentation prevails over erosion (MRVBF: 2.84–5.95).
CL_3C	Potentially azonal – not influenced by groundwater	Medium to very inclined slopes (7.8–17.3°), including steep slopes (over 17°) with moderately favourable to very mildly unfavourable terrain texture (the portion of evenly shaped terrain and terrain relief abnormalities in 1 km^2 area falls into medium values (47–57) – more or less evenly shaped both concave and convex terrain shapes (NEG_O: 76.8–82.5°). Slope height ranges between 87–134 m. From the perspective of pedogenetic processes, erosion prevails over sedimentation (MRVBF: 0.00–0.01).

Appendix 3: The name and characteristics of clusters for the Hercynicum spatial frame (the interval of values represents the lower (25 %) and upper (75 %) quartile of 1,000 randomly generated points)

Cluster	Name	Description based on significant factors
CL_1H	Potentially zonal	Mild to medium inclined slopes (3.5–7.9°) with a favourable terrain texture (the portion of evenly shaped terrain and terrain relief abnormalities in 1 km^2 area falls into medium value range, 37–49). The slopes are mildly concave (NEG_O: 85.2–87.7), and slope height ranges between 19–34 m. From the perspective of pedogenetic processes, erosion is prevalent over sedimentation, or both processes are evenly present (MRVBF: 0.08–0.70).
CL_2H	Potentially azonal – influenced by groundwater table	Flat surfaces (0.6–2.3°) up to 3° slope gradient with very favourable terrain texture (the portion of evenly shaped terrain and terrain relief abnormalities in 1 km^2 area is low, 20–40), with a prevalence of flat terrain shapes (NEG_O: 88.2–89.3°). Slope height ranges between 13–20 m. From the perspective of pedogenetic processes, sedimentation is prevalent over erosion (MRVBF: 1.90–4.94).
CL_3H	Potentially azonal – not influenced by groundwater table	Medium to very inclined slopes (5.4–13.4°), including very inclined slopes (up to 15°) with moderately favourable terrain texture (the portion of evenly shaped terrain and terrain relief abnormalities in 1 km^2 area falls into medium values range, 42–51). Terrain shapes are more or less evenly concave and convex (NEG_O: 80.5–84.6°), and slope height ranges between 31–105 m. From the perspective of pedogenetic processes, erosion is prevalent over sedimentation (MRVBF: 0.00–0.10).

Appendix 4: Statistically insignificant environmental factors‘ differences in the model clusters

CLUSTER	CL_1H	CL_2H	CL_3H	CL_1C	CL_2C	CL_3C	CL_1CR	CL_2CR	CL_3CR
CL_1H	*	-	-	-	-	-	T, H, M	S, T, N, H	-
CL_2H	-	*	-	-	S	-	-	-	-
CL_3H	-	-	*	T	-	M	-	-	M
CL_1C	-	-	T	*	-	-	H, M	-	-
CL_2C	-	S	-	-	*	-	-	S, H	-
CL_3C	-	-	M	-	-	*	-	-	-
CL_1CR	T, H, M	-	-	H, M	-	-	*	-	-
CL_2CR	-	S, T, N, H	-	-	S, H	-	-	*	
CL_3CR	-	-	M	-	-	M	-	-	*

Explanatory notes: S – SLP, T – TEX, N – NEG_O, H – SLP, M – MRVBF. In case the value is missing and the field is marked with a dash (-), a statistically significant difference is present