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Ekológia (Bratislava) Vol. 35, No. 3, p. 263–278, 2016
DOI:10.1515/eko-2016-0021

SPATIAL HETEROGENEITY OF MECHANICAL IMPEDANCE OF ATYPICAL CHERNOZEM: THE ECOLOGICAL APPROACH

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Abstract

Zhukov A., Gadorozhnaya G.: Spatial heterogeneity of mechanical impedance of atypical chernozem: the ecological approach. Ekológia (Bratislava), Vol. 35, No. 3, p. 263–278, 2016.

In this research paper, the spatial heterogeneity of mechanical impedance of a typical chernozem was investigated. The distance between experimental points in the mechanical impedance space was explained by means of multidimensional scaling. Spearman's rank correlation coefficients between dissimilarity indices and gradient separation with different data transformation methods revealed that the use of log-transformed data and Horn-Morisita distance was the most appropriate approach to reflect the relationship between the mechanical impedance of soil and ecological factors. A three dimensional variant of multidimensional scaling procedure was selected as the most appropriate decision. Environmental factors were estimated with the use of phytoindicator scales. Broad, medium and fine-scale components of spatial variation of mechanical impedance of soil were extracted using the principal coordinates of neighbour matrices method (PCNM). In the extracted dimensions, statistically significant phytoindicator scales were found to describe variability from 8 to 33%. Dimension 1 correlated with a thermal climate indicator value, a hygromorphs index, an abundance of steppe species and meadow species. Dimension 2 correlated with a continental climate indicator value, carbonate content in the soil and the soil trophicity index (capacity of the soil for plant nutrition). Dimension 3 correlated with acidity, humidity and cryoclimate indicator values. Variation partitioning results revealed that environmental factors and spatial variables explained 47.8% of the total variation of the dimensions. Purely environmental component explained 18.2% of total variation. The spatial component and spatially structured environmental fractions explained 43.6%. The broad-scale spatial component explained 26.4% of dimensional variation, medium-scale – 6.7% and fine-scale – 5.7%. As a result of regression analysis, the broad-scale spatially structured environmental fractions were found to be connected with variability of moisture and thermal climate indicator values. The medium-scale component was revealed to be connected with variability of moisture, thermal climate, total salt regime and aeration of soil indicator value. The fine-scale component was connected with carbonate content in the soil, acidity and humidity indicator values.

Key words: soil compaction, phytoindication, principal coordinates of neighbour matrices method, multidimensional scaling.

Introduction

The spatial heterogeneity of soil, to a large extent, defines the functional features of the soil. The heterogeneity of physical and chemical properties and soil-physical processes may be determined at each hierarchical level of the soil organisation (Borcard, Legendre, 1994; Shin, Milanovsky, 2001; Dray et al., 2006; Jiménez et al., 2014). The heterogeneity of soil, in a vertical direction, is caused by the distance from the surface and the intensity of the soil formation process. The horizontal spatial heterogeneity of soil properties is connected with the patchwork structure of ecosystems (Karpachevskij et al., 2007; Bobrovskij, 2010). The borders between elementary units of this mosaic may be defined by the criterion of changes in dominant plant species. In some cases of boreal forest plants, the dominant mosaic was shown to reflect realistically spatial variation in soil properties (Lukina, Nikonov, 1996, 1998; Lukina et al., 2002, 2006; Orlova et al., 2003). However, the vital functions of a vegetative community are not a unique factor of soil heterogeneity. Biotic component, hydrothermal, lithological and morphological factors may also contribute to the formation of heterogeneity of soil conditions (Samsonova, 2008; Zagulnova et al., 2010; Medvedev, 2009). The multifactorality of conditions makes it difficult to achieve a uniform approach to identification of soil heterogeneity and its functional linkages. Procedures of differentiation of elements of heterogeneity and their results differ considerably depending on which traits or properties are selected to define heterogeneity. The soil can be non-uniform on the basis of acidity, particle and aggregate size distribution, humidity, chemical content, etc. (Wright, 1998; Goncalves et al., 1999; Clemens et al., 1999; Selles et al., 1999, Samsonova, 2008; Soracco et al., 2010; Medvedev, Melnik, 2010). Borders have different features and their delineation in various places depends on what criteria are used for defining heterogeneity of the soil space. Therefore, integrated characteristics of soil properties are the most effective criteria to be used to differentiate soil space. Such characteristics should reflect composite changes of soil space. Soil compaction is such a soil property. Soil compaction will produce mechanical impedance. Mechanical impedance is a high-informative index which reflects the physical condition of a soil body (Zhukov, 2015; Zadorozhnaya, 2012; Medvedev, 2009). Soil compaction alters soil structure and hydrology by increasing bulk density, breaking down aggregates, decreasing porosity, aeration and infiltration capacity, and by increasing soil strength, water run-off, erosion and water logging (Kozlowski, 1999; Startsev, McNabb, 2000; Godefroid, Koedam, 2004). The spatial variation of mechanical impedance of the soil significantly correlates with indicators such as bulk density, electrical conductivity, relative ground cover of living plants, phytomass and aggregate particle distribution (Bondar, Zhukov, 2011; Tryfanova et al., 2014). Soil compaction depends on soil humidity, texture, organic contents and the composition of exchangeable cations (Medvedev, 2009). This makes mechanical impedance a promising approach in soil and agronomical researches (Grunwald et al., 2001; Hamza, Anderson, 2005; Ramirez-Lopez et al., 2008; Serafim et al., 2008; Medina et al., 2012).

As a rule, the character of impact of soil compaction on plants was considered in this research (Montagu et al., 2001; Bayhan et al., 2002; Grzesiak et al., 2002; Parackova, Zaujec, 2001; Langmaack et al., 2002; Rosolem et al., 2002; Godefroid, Koedam, 2003, 2004). Soil mechanical impedance was found to correlate with Ellenberg's light indicator values. However, distinctions in mean nitrogen index between plants and variations in the degree of tolerance to soil compaction were not revealed (Godefroid, Koedam, 2004). Phytoindicator scales can be considered as markers of environmental properties. Correctly recorded vegetation plots are less influenced by spatial and temporal variability than single field measurements of environmental factors (Jongman et al., 1987; Horsák et al., 2007). Ellenberg phytoindicator scales have successfully been applied to the description of molluscs' habitats preferences (Horsák et al., 2007, Schenková et al., 2012). It is noteworthy that direct comparison of plant indicator values with measured data has shown that the name of a factor does not always reflect its real content clearly (Schaffers, Sykora, 2000, Horsák et al., 2007).

Plants and animals are not only influenced by soil compaction but also actively affect this property of soil. Both earthworms and plant roots can work to break up soil, thereby ameliorating the negative impacts of soil compaction and improving their own biological habitat (Capowiez et al., 2009). Thus, the features of plant cover expressed in terms of phytoindicator scales can act as indicators of soil properties defining a spatial variation of mechanical impedance of the soil, and reflect features of direct influence of plants on mechanical impedance of the soil.

The aim of this paper is to reveal the spatial component of variation in the mechanical impedance of a typical chernozem, and the impact of plant cover and environmental factors expressed in terms of phytoindicator values on the formation of heterogeneity of chernozem compaction indicated by the mechanical impedance.

Material and methods

Typical chernozem was studied on the steppe site, adjoining a South-East slope of a ravine Kamyanuvasta (in the southern part of the city of Dnepropetrovsk, Ukraine), 48°23'11"N, and 48°23'11" E. The data was collected on April 19th, 2013. The investigated plot represented a regular grid with 7×15 sample points. The distance between sampling points was 3 m. The size of the plot was 18×42 m.

Measurements of mechanical impedance of the soil were carried out in field conditions to a depth of 100 cm at intervals of 5 cm. Mechanical impedance of the soil was recorded using a cone-penetrometer (Eijkelkamp Agrisearch Equipment, the Netherlands) (Grunwald et al., 2001; Medina et al., 2012; Betz, 2013; Moiseev, 2013; Zhukov, Zadorozhnaya, 2015; Zhukov, 2015). The average error of device measurement results was ± 8%. Measurements of mechanical impedance of the soil were made by a cone of cross-section 2 of cm^2 in each cell of range.

I. P. Didukh (Didukh, 2011, 2012) phytoindicator scales were used. According to Didukh phytoindicator scales, the following ecological factors were revealed. The group of edaphic factors were presented by *Hd* – soil humidity, *fH* – variability of moisture, *Ae* – aeration of soil, *Rc* – acidity, *Sl* – total salt regime, *Ca* – carbonate content in soil and *Nt* – nitrogen content. The group of climatic factors were presented by *Tm* – thermal climate, *Om* – humidity, *Cr* – cryoclimate and Kn – climate continentality. Besides these specified factors, Lc – light in plant community was considered as a microclimatic scale. A system of plant ecomorphs was used according to Belgard (1950) and Tarasov (2012). The plant ecomorphs were represented by coenomorphs, hygromorphs, trophomorphs and heliomorphs. Coenomorphs were represented by steppe species, meadow species, psammophytes (plants living in sand), silvants (forest species) and ruderants (ruderal species). Steppe and forest species constituted a major share of the vegetative cover within the experimental plot (76.51 and 16.39% accordingly), therefore, these ecomorphs were used as soil mechanical impedance predictors (variables St and Pr represent the ecomorphs' projective cover, %). Hygromorphs were represented by xerophytes (humidity level 1), mesoxerophytes (humidity level 2), xeromesophytes (humidity level 3), mesophytes (humidity level 4) and hygromesophytes (humidity level 5). The humidity index (*Hygr*) was estimated as:

$$Hygr = \frac{\sum_{i=1}^{i=N}(i \times P_i)}{100},$$

where i - humidity level; P_i - hygromorphs projective cover of corresponding humidity level.

Trophomorphs were represented by oligotrophs (trophicity level 1), mesotrophs (trophicity level 2) and megatrophs (trophicity level 1). The trophicity index (*Troph_B*) was estimated as:

$$Troph\_B = \frac{\sum_{j=1}^{j=N}(j \times P_j)}{100},$$

where j - trophicity level; P_j - trophomorphs projective cover of corresponding trophicity level.

Plants may be classified ecologically, according to their requirement of light – those needing full sunlight for good growth are known as heliophytes, while those growing best in shade are known as sciophytes. Such ecological groups are named as heliomorphs (Belgard, 1950). Heliomorphs within the plot were represented by heliosciophytes (solar radiation level 2), sciophytes (solar radiation level 3), and heliophytes (solar radiation level 4). The solar radiation index (*Hel*) was estimated as:

$$Hel = \frac{\sum_{z=1}^{z=N}(z \times P_z)}{100},$$

where z - solar radiation level; P_z - heliomorphs projective cover of corresponding solar radiation level.

To decrease the dimension of the soil mechanical impedance space, non-metric multidimensional scaling was applied (Minchin, 1987; Shitikov et al., 2003; Tolstova, 2006; Novakovsky, 2008). As measures of distance between sample points in the soil mechanical impedance space, the following metrics were used: Euclidean, Manhattan, Gower, Bray-Curtis, Kulczynski, Morisita, Horn-Morisita, Cao, Jaccard, Mountford, Raup-Crick, Canberra and Chao (Oksanen, 2011). The selection of appropriate distance metric and the variants of primary data preliminary transformation was made on the basis of Spearman's rank correlation coefficients between dissimilarity indices and gradient separation (Legendre, Gallagher, 2001). Principal coordinates of neighbour matrices analysis (PCNM) was applied for the assessment of spatial structure in soil mechanical impedance variation (Borcard, Legendre, 2002). It is based on the construction of the modified truncated matrix of distances between sampling points, the analysis of its main coordinates (Borcard, Legendre, 2002) and the selection of the PCNM-variables as the best way of describing the studied properties of an object of the research (Borcard et al., 2004; Dray et al., 2006; Legendre et al., 2009). To reduce risk of incorporating too many variables, the forward selection procedure was used (Blanchet et al., 2008). Variation partitioning enabled us to determine the various unique and combined fractions of variation explained in the soil mechanical impedance data by the environmental and spatial (PCNMs variables) data (Borcard et al., 1992). For this analysis, soil mechanical impedance data was de-trended before the analysis. We adjusted the R^2-values to account for the number of sampling sites and explanatory variables, as unadjusted R^2-values are biased (Peres-Neto et al., 2006), and reported the adjusted values throughout. The chosen environmental variables (env – phytoindicator values in ecomorphs indices) and spatial variables (PCNMs) were analysed with the powerful, partial redundancy analysis (pRDA) method. A pRDA allows the total variation of a data matrix in each plot to be partitioned into fractions that represent the contribution of the pure environmental frac-

T a b l e 1. Mechanical impedance of soil : Descriptive statistics.

Layers depth, cm	Mean, MPa	Confidence intervals		CV,%
		– 95%	+ 95%	
0–5	1.34	1.28	1.40	22.77
5–10	1.32	1.24	1.40	31.40
10–15	1.29	1.21	1.37	30.42
15–20	1.32	1.27	1.38	20.46
20–25	1.32	1.28	1.37	17.89
25–30	1.36	1.32	1.41	18.42
30–35	1.38	1.32	1.43	19.69
35–40	1.45	1.39	1.51	21.46
40–45	1.53	1.47	1.60	21.83
45–50	1.60	1.53	1.66	21.36
50–55	1.62	1.55	1.69	21.93
55–60	1.70	1.62	1.78	24.15
60–65	1.82	1.74	1.91	23.06
65–70	1.86	1.78	1.94	22.38
70–75	1.82	1.74	1.91	24.96
75–80	1.80	1.69	1.90	29.28
80–85	1.79	1.69	1.89	28.26
85–90	1.79	1.69	1.89	28.96
90–95	1.78	1.68	1.88	28.53
95–100	1.79	1.69	1.89	28.51

tion, the spatially structured environmental fraction (shared fraction), the pure spatial fraction and the unexplained fraction (Peres-Neto et al., 2006; Borcard et al., 2011; Gao et al., 2014). The significance of each source of variation was tested with a Monte Carlo permutation test (999 permutations). The R-language vegan (Oksanen et al., 2007) and PCNM (Dray et al., 2006) libraries were used for calculation.

Results

The present research was carried out in the spring after the snow melted, in conditions of high soil humidity and hence, low values of its mechanical impedance. Mean values of mechanical impedance increased with depth, from 1.34 MPa (in the layer of 0–5 cm) to 1.86 MPa (in the layer of 70–75 cm), and then again to 1.79 MPa at a level of 100 cm downwards on a profile of slight decrease (Table 1). The coefficient variation was the highest in the layers of 5–10 and 10–15 cm from the surface (30.42–31.40%). At greater depths, variability of mechanical impedance decreased to values of 17.86% at the level 20–25 cm, and again increased to 28.96% in the deepest studied layers.

Spearman's rank correlation coefficients between dissimilarity indices and gradient separation with different data transformation methods have revealed that usage of log-transformed data and Horn-Morisita distance is the most appropriate approach to reflect the relationship between soil mechanical impedance and ecological factors (Table 2). In further calculations, the experimental data will be used in the above-mentioned transformed way.

T a b l e 2. Spearman's rank correlation coefficients between dissimilarity indices and gradient separation with different data transformation methods.

Distance	Data transformation methods										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Euclidean	0.13	0.17	0.15	0.20	0.17	0.16	0.19	0.17	0.21	0.20	0.21
Manhattan	0.12	0.15	0.14	0.19	0.14	0.14	0.18	0.15	0.20	0.19	0.20
Gower	0.15	0.16	0.15	0.19	0.15	0.15	0.19	0.15	0.20	0.19	0.20
Bray-Curtis	0.13	0.16	0.14	0.19	0.16	0.15	0.19	0.17	0.20	0.19	0.20
Kulczynski	0.14	0.16	0.15	0.19	0.17	0.16	0.19	0.19	0.20	0.19	0.20
Morisita	–	–	–	0.05	-0.09	0.03	-0.05	-0.10	-0.06	-0.02	-0.03
Horn-Morisita	0.19	**0.23**	0.21	0.19	0.22	0.21	0.19	0.22	0.21	0.20	0.22
Cao	0.17	0.20	0.17	–	0.17	0.17	0.21	0.19	0.22	0.22	–
Jaccard	0.13	0.16	0.14	0.19	0.16	0.15	0.19	0.17	0.20	0.19	0.20
Mountford	–	–	–	–	–	–	–	0.05	–	–	–
Raup-Crick	–	–	–	–	–	–	–	0.02	–	–	–
Canberra	0.15	0.17	0.15	0.20	0.15	0.15	0.20	0.16	0.20	0.20	0.20
Chao	–	–	–	–	–	–	–	0.10	–	–	–
Mahalanobis	0.15	0.18	0.16	0.14	0.15	0.15	0.14	0.15	0.16	0.14	0.15

Notes: 1 – untransformed data; 2 – log-transformed data; 3 – square-root transformed data; 4 – divided by margin total; 5 – divided by margin maximum; 6 – divided by margin maximum and multiplied by the number of non-zero items, so that the average of non-zero entries is one; 7 – normalised (margin sum of squares equal to one); 8 –standardised values into range 0–1; 9 – Hellinger transformation; 10 – χ^2-transformation; 11 – Wisconsin transformation.

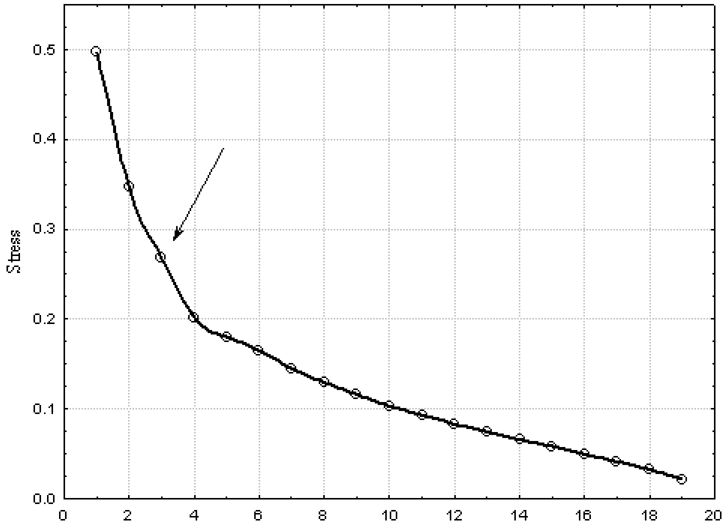


Fig. 1. Stress versus number of dimensions screen diagram. Arrow shows optimal number of dimension.

Table 3. Weighted average scores of mechanical impedance value in soil layers for ordination configuration.

Soil layers, cm	Dimensions		
	MDS1	**MDS2**	**MDS3**
0–5	0.88	–1.58	0.04
5–10	1.92	–2.81	0.34
10–15	2.46	–3.24	1.16
15–20	0.30	–1.54	–0.65
20–25	–0.44	–0.73	–0.96
25–30	–1.14	–0.72	–1.69
30–35	–1.82	–0.28	–1.32
35–40	–1.43	–0.07	–0.94
40–45	–2.08	–0.08	–0.68
45–50	–1.94	–0.13	0.37
50–55	–1.45	0.35	0.26
55–60	–1.29	0.48	1.07
60–65	–0.75	0.44	1.31
65–70	–0.52	0.55	1.20
70–75	–0.29	0.82	0.99
75–80	0.72	1.12	0.81
80–85	1.33	1.24	0.42
85–90	1.89	1.38	–0.45
90–95	1.97	1.42	–0.83
95–100	1.90	1.43	–0.87

Stress is a goodness-of-fit statistic in multidimensional scaling based on the differences between the actual distances and their predicted values. One of the goals of multidimensional scaling analysis is to keep the number of dimensions as small as possible. The usual technique is to solve the multidimensional scaling problem for a number of dimension values, and adopt the smallest number of dimensions that achieves a reasonably small value of stress. An appropriate number of dimensions were chosen by performing ordinations of progressively higher number of dimensions. A stress versus number of dimensions scree diagram was then plotted, on which one could identify the point beyond which additional dimensions do not substantially lower the stress value (Fig. 1). A three dimension variant of multidimensional scaling procedure was selected as the most appropriate decision.

The three dimensions selected after the non-metric multidimensional scaling (NMDS) were interpreted by computing weighted average scores of mechanical impedance value in soil layers for ordination configuration (Table 3).

Dimension 1 reflected opposite dynamics of soil mechanical impedance at depths of 20–75 cm compared to those of the layers above and below the specified layer. Dimension 2 reflected opposite dynamics of soil mechanical impedance above and below the level 50 cm. Dimension 3 reflected opposite dynamics of soil mechanical impedance in the layers 0–15 cm and 45–85 cm on the one hand, and in the layers 15–45 and 85–100 cm on the other hand.

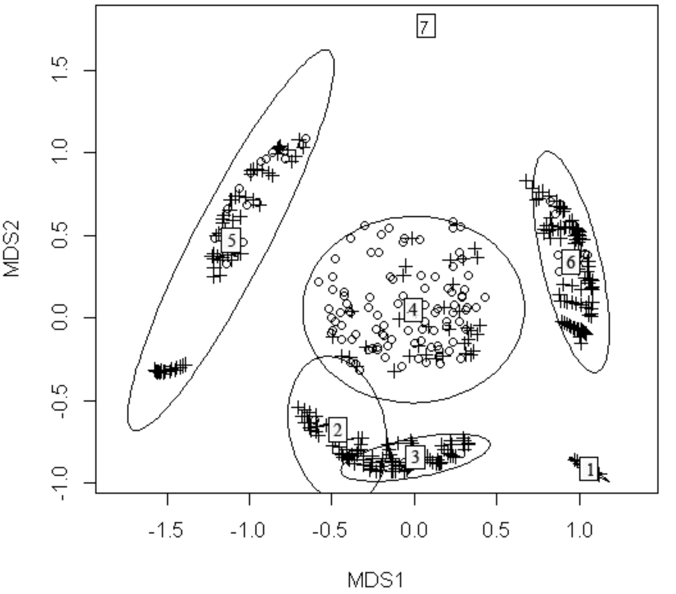


Fig. 2. Spatial variation of the dimensions MDS1 – MDS3.

T a b l e 4. Fitting environmental factors onto an ordination.

Predictors	**MDS1**	**MDS2**	**MDS3**	**r²**	**Pr(>r)**	**Significance codes**
Phytoindicator values						
Hd	0.37	0.18	−0.91	0.14	0.00	**
fH	−0.44	0.38	−0.82	0.09	0.02	*
Rc	−0.36	−0.58	0.73	0.14	0.00	**
Sl	−0.98	0.05	−0.17	0.08	0.04	*
Ca	−0.65	0.70	0.31	0.27	0.00	***
Nt	−0.43	0.19	−0.88	0.10	0.02	*
Ae	−0.25	0.09	0.96	0.06	0.09	.
Tm	−0.86	−0.39	0.34	0.11	0.00	**
Om	−0.78	−0.62	−0.06	0.07	0.06	.
Kn	0.70	−0.63	0.33	0.12	0.01	**
Cr	0.79	−0.46	−0.41	0.04	0.28	
Lc	1.00	−0.07	0.03	0.08	0.04	*
Ecomorphs indexes						
Hygr	−0.91	−0.35	0.21	0.46	0.00	***
Troph_B	0.49	−0.18	−0.85	0.13	0.00	***
St	0.30	0.73	0.62	0.13	0.00	**
Pr	−0.29	−0.73	−0.62	0.13	0.00	**
Hel	0.85	0.08	−0.52	0.32	0.00	***

Notes: Significance codes: ‘***’ – <0.001; ‘**’ – <0.01; ‘*’ – <0.05.

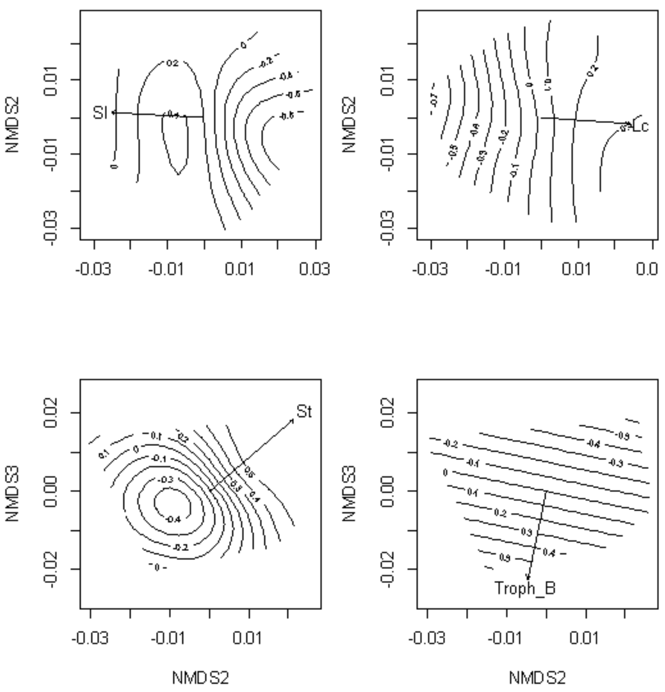


Fig. 3. Smoothing surface for some ecological factors within ordination diagram.

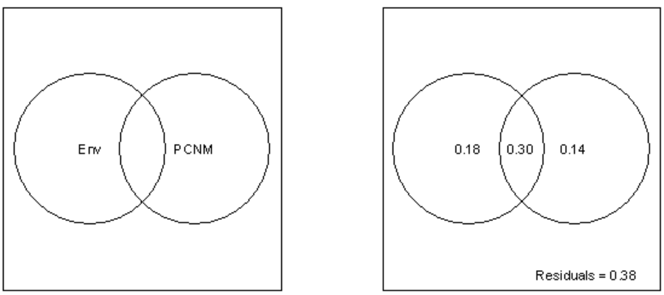
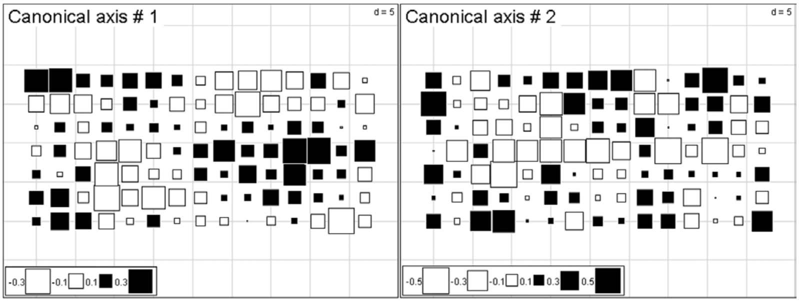


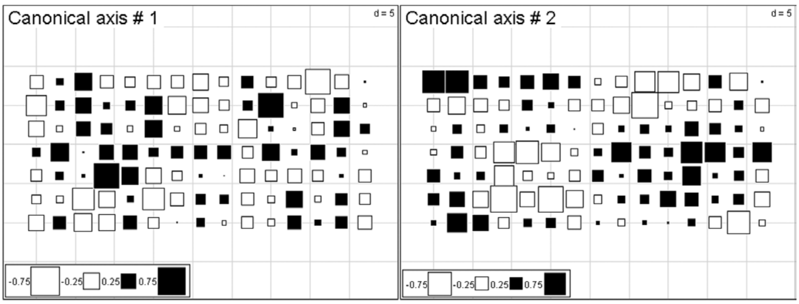
Fig. 4. Variation partitioning of soil impedance data after multidimensional scaling by partial redundancy analysis (pRDA). Pure environmental [Env], pure spatial [PCNM] and shared fractions [intersection of Env and PCNM] are provided. **P < 0.01.

Spatial variation of the dimension MDS1 – MDS3 is presented in Figure 2. The dimensions have been explained in terms of phytoindicators values (Table 4). Statistically significant phytoindicator scales described variability of dimension from 8 to 46%. Dimension MDS1 was found to be predominantly affected by abundance of steppe plants , soil humidity, light in plant community, trophicity and solar radiation (positive sign of influence), and abundance of meadow plants, humidity index, thermal climate and aeration of soil (negative sign of influence). Dimension MDS2 was predominantly affected by steppe plants, nitrogen content, carbonate content in soil, variability of moisture (positive sign of influence), and climate continentality, trophicity and meadow plants (negative sign of influence). Dimension MDS3 was predominantly affected by cryoclimate, solar radiation index and light in plant community (positive sign of influence), and acidity, humidity and aeration of soil (negative sign of influence).

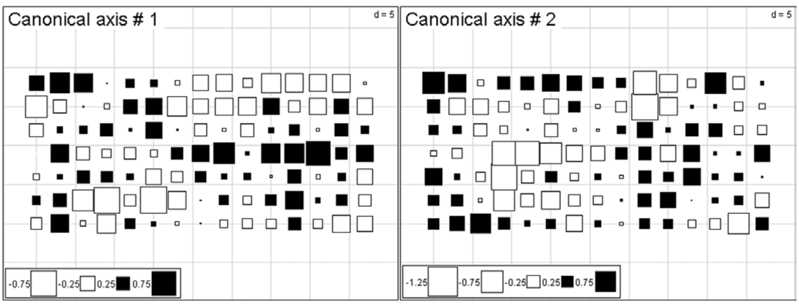
Fitting environmental factors onto an ordination (Table 4) provided a description of linear aspect of the impact of factors on the studied variables. The most complicated relations may be reflected by fitting a smooth surface for a given variable, and plotting the result on



Broad scale component



Medium scale component



Fine scale component

Fig. 5. Spatial variation of the canonical axes obtained as a result of the redundancy analysis of various scale spatial components.

an ordination diagram. For example, smoothing surfaces for some ecological factors such as total salt regime, light in community, steppe plants and trophicity index were presented to demonstrate that a linear model is not always adequate to describe relations between the soil mechanical impedance dimension and the ecological factors (Fig. 3).

As a result of the PCNM-analysis, 55 PCNM-variables were obtained, which had positive Moran's indices. These variables described R^2_a = 54.8% of dimension variability obtained after multidimensional scaling of soil mechanical impedance data (F = 3.29, p = 0/001). After forward selection procedure, the 15 most informative PCNM-variables were selected, which described R^2_a = 42.9% of dimensions variability (F = 6.22, p = 0.001). Variation partitioning allowed us to establish that environmental and spatial factors described 47.8% of variability of the dimensions (F = 4.17, p = 0.001) (Fig. 3). The purely environmental component explained 18.2% of the total variation. The spatial component and spatially structured environmental fractions explained 43.6% of variability (F = 6.22, p = 0.001). The purely spatial component explained 13.9% of variability of the dimensions (F = 3.76, p = 0.001).

Spatial variables were grouped into three components: broad scale (PCNM variables 1, 4, 7, 8 and 9), medium scale (11, 26, 27, 31 and 35) and fine scale (36, 46, 48, 54 and 55). After redundancy analysis of broad scale, medium scale and fine scale components, three significant spatial submodels were computed. Each submodel was represented by two significant canonical axes (Fig. 4). The broad scale component was stated to describe R^2_a = 26.4% of soil impedance dimension (F = 7.23, p = 0.001), medium scale component described R^2_a = 6.7% (F = 2.49, p = 0.001), and fine scale components described R^2_a = 5.7% (F = 2.57, p = 0.006).

T a b l e 5. Regression of spatial submodel on environmental variables (only significant regression coefficients are presented, p < 0.05).

Environmental factors	**Broad scale component**		**Medium scale component**		**Fine scale component**	
	CA1 R^2_a =0.48	CA2 R^2_a =0.07	CA1 R^2_a =0.12	CA2 R^2_a =0.55	CA1 R^2_a =0.37	CA2 R^2_a =0.35
Phytoindicator values						
Hd	–	–	0.024	–	–	–
fH	0.011	0.023	–0.017	0.033	–	0.049
Rc	0.030	–	–	0.062	0.037	0.047
Sl	–0.021	–	0.033	–0.040	–	–0.053
Ca	–0.036	–	–	–0.100	–0.069	–0.074
Nt	–	0.028	–	–	–	0.039
Ae	–0.010	–	–0.017	–0.037	–0.032	–
Tm	–0.017	–0.024	0.024	–0.043	–	–0.059
Om	0.012	–	–	0.039	0.026	0.030
Kn	–	–	–	–	–	–
Cr	–	–	–	0.021	–	–
Lc	0.012	–	–	0.027	–	0.030
Ecomorphs indexes						
Hygr	–	–0.026	0.035	–	–	–0.043
Troph_B	–	–	–	–	–	–
St	–	–	–	–0.444	–	–
Pr	–	–	–	–0.439	–	–
Hel	–	–	0.030	–	0.030	–

Canonical axes include both spatial and environmental aspects of the dimensional variation of mechanical impedance of the soil. To identify the environmental variables related to soil mechanical impedance dimensions on all the scales, the three spatial submodels obtained were submitted to multiple regression analyses, with phytoindicator values and ecomorph indices as explanatory variables (Fig. 5, Table 5). Regression analysis was able to explain 48 and 7% of the variation of broad scale components CA1 and CA2, respectively. The low ability of the environmental variables to explain CA2 variation allowed us to consider it as almost entirely spatial. The most prominent environmental predictors explaining the broad scale spatial submodel were variability of moisture, acidity, carbonate content in the soil, thermal climate, nitrogen content and humidity index. Environmental explanatory variables explained 12 and 55% of medium scale CA1 and CA2, respectively. For medium scale, CA1 significant predictors were Hd, Sl, Tm, Hygr, Hel (positive sign) and fH, Sl (negative sign). Medium scale CA2 was sensitive to the total plant cover projection, as the regression coefficients of both steppe plants and meadow plants had an equal sign. Total plant cover projection correlated positively with soil mineralization level (Sl, Ca), aeration of soil and thermal climate. On the other hand, total plant cover correlated negatively with fH, Rc, Om, Cr and Lc. Fine scale components CA1 and CA2 were explained to a large extent by environmental factors (37 and 35%, respectively). The most prominent environmental predictors explaining fine scale CA1 were Rc, Om, Hel (positive sign) and Ca, Ae (negative sign). It is worth noting that a list of significant regression coefficients for broad scale CA1, medium scale CA2 and fine scale CA2 resembled each other closely with slight differences.

Discussion

As a result of our research, the hierarchical structure of variations in mechanical impedance variation of chernozem dependent on both ecological factors and spatial components was revealed. For this purpose, environmental factors were indicated by means of plants indicator values (Didukh, 2011, 2012) and indices based on Belgard's system of ecomorphs (Belgard, 1950). The relationship between soil compaction and plants have a sensitive nature. On the level of spatial point, soil compaction reflects growing conditions of a single plant organism (Montagu et al., 2001; Bayhan et al., 2002; Grzesiak et al., 2002; Parackova, Zaujec, 2001; Langmaack et al., 2002; Rosolem et al., 2002; Godefroid, Koedam, 2003, 2004). On a higher spatial level, plants are able to indicate a considerable variety of ecological factors, both edaphic and climatic (Didukh, 2011). The phytoindicator approach is advantageous not only because direct instrumental measurement of the soil properties is quite time- consuming and labour- intensive (Ertsen et al., 1998; Zagulnova et al., 1998; Schaffers, Sykora, 2000; Zagulnova, Tihonova, 2010). The specificity of plant indication is that the temporal variation of ecological regimes is reflected in an integrated form (Didukh, Pluta, 1994). For this reason, the spatial variation of indicator values presents stable patterns of ecological conditions. Such ecological circumstances may affect the spatial variation of the mechanical impedance of soil. Also, the architectonic of plants' root systems has to be considered as a factor which impacts the physical condition of soil. This impact may be shown in terms of phytoindicator values and ecomorph indexes (Ramensky et al., 1956; Matveev, 2003; Zagulnova, Tihonova, 2010).

The legitimacy of application of phytoindicator scales for characterising ecological factors is proved by a considerable amount of research. The correlation between direct measurement of ecological factors and plant indicator values has been shown to be statistically significant (Didukh, Pluta, 1994; Zagulnova et al., 1998; Ertsen et al., 1998; Schaffers, Sykora, 2000). In our investigation, phytoindicator values acted as a link between the vegetation structure and the mechanical impedance of the soil.

The data on mechanical impedance of soil have been subjected to the procedure of multidimensional scaling. Many experts recognise that this method yields the most adequate results, especially in large blocks of data with strong noise (random deviations) (Prentice, 1977; Minchin, 1987; Shitikov et al., 2003; Tolstova, 2006; Novakovsky, 2008). It is very important to select an appropriate distance measure between the sample points and the previous data transformation method because the results of multidimensional scaling depend greatly on this selection. To resolve this matter, Spearman's rank correlation coefficients between dissimilarity indices and gradient separation with different data transformation methods were calculated. Horn-Morisita distance with log-transformed data was found to produce a matrix that exhibited the highest correlation with environmental factors. The Horn-Morisita index is one of the more popular geometric angular measures, which gives the cosine of an angle between a pair of standardised vectors (Magurran, 2004). Cronbach and Gleser (1953) explained that configurations of data profiles can be described along three dimensions – elevation scatter, and shape. The Horn-Morisita index is sensitive to scatter and shape of the soil's mechanical distribution profile. This result is very important because it shows that the form of the profile is most significant in reflecting the specifics of connection with environmental factors. In this regard, elevation as another aspect of profile may be mentioned as being the measure of total soil compaction. It appears that the total level of mechanical compaction of the soil is a highly variable property in contrast to soil profile form, which is quite invariant. Because of this invariant behaviour of the soil, the mechanical impedance profile distribution provides a statistically significant connection with environmental factors indicated by plants.

Each dimension derived after multidimensional scaling, presents a special pattern of soil mechanical impedance profile within the soil layer. The three dimension solution has been found to be optimal for reproducing initial distance matrix. That is why three profile patterns may be recognised for variability of soil impedance.

The three dimensions show different tendencies of variation in the mechanical impedance of the soil within certain parts of the soil layer. Dimension 1 reflects soil differentiation into three strata. The boundary between them runs at depths of 20–25 and 70–75 cm. The internal layer demonstrates an opposite tendency of changes in mechanical impedance of the soil in comparison with the upper and the lower layers. Soil differentiation into two strata with opposite mechanical impedance dynamic is connected with dimension 2. The boundary between these strata runs at a depth of 50–55 cm. Like dimension 1, the dimension 3 is connected with soil differentiation into three strata. The boundary between them runs at depths 10–15 and 40–45 cm. It is important that the dimension derived after multidimensional scaling procedure provides an opportunity to consider soil mechanical impedance variation in a vertical direction, and simultaneously, this dimension may be projected in a horizontal plane to be explained in terms of ecological factors. In other words, application of the multidimensional scaling provides integration of the soil mechanical impedance variation, both in vertical and horizontal directions.

The dimension 1 is predominantly affected by moisture gradient. This result fully corresponds with a strong negative correlation between soil mechanical impedance and soil moisture content (Medvedev, 2009). Dry soil conditions are indicated by light in plant community values and solar radiation index. It is important that the driest conditions correspond to prevalence of steppe plant species, and the moistest conditions correspond to the prevalence of meadow plant species.

Along with other indicator values, the steppe plant and meadow plant canopy projection cover is the main important index to explain dimension 2. The antagonistic relation between steppe and meadow coenosis may be concluded to lead to considerable variation in soil mechanical impedance. This result may be correct in relation to dimension 3. But in this case, the nutrient dynamic processes are overlapped by the coenosis relationships.

It is noteworthy that linear relationships between soil mechanical impedance and ecological factors are not always appropriate for modelling. Smoothing the surface for ecological factors within an ordination diagram has revealed quite a complicated reaction of the soil's mechanical impedance to the influence of ecological factors in some cases.

The principal coordinates of neighbour matrices (PCNMs) have been used as explanatory variables to analyze the spatial variation of the dimension obtained after multidimensional scaling as response variables. Environmental and spatial factors were able to explain up to 47.8% of the dimensions' variability. The most important part of the variation explained belonged to the spatial component and spatially structured environmental fractions. This result is quite expected if the regular distribution of plant species within the studied polygon is taken into account. The purely environmental component may be considered as a direct influence of the plants' organisms on soil mechanical resistance. The purely spatial component in turn may be seen as a result of autonomous processes of the variation in mechanical impedance of the soil.

Spatial and spatially structured environmental variation of mechanical impedance has a complicated nature, which may be shown to be divided into three hierarchical components. The most important broad scale component explains 26.4%, which is considerably greater than the medium scale (6.7%) and fine scale (5.7%) components. Multiple regressions have revealed that all hierarchical submodels may be explained with phytoindicator values and ecomorphs indexes as explanatory variables. Only the broad scale canonical axis 2 may be considered as purely spatial.

Conclusion

Mechanical impedance of the soil is a very important and ecologically relevant soil property. Traditionally, this property has been considered as a factor influencing the growth rate of plant roots, or as a marker of living conditions of soil animals. In our research, another aspect of mechanical impedance of the soil has been treated. We have attempted to investigate spatial variation of mechanical impedance of the soil. The phytoindicator values and ecomorphs indexes, both derived from information about plant cover, were chosen as the ecological factors which influence mechanical impedance of the soil. Plant indicator values have been shown to be capable of explaining the mechanical impedance of the soil at the different levels of spatial hierarchy.

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