THE RELATIONSHIP BETWEEN SOIL HETEROGENEITY AND CELLULOLYTIC ACTIVITY

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Abstract

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This article examines the relationship between soil heterogeneity and cellulolytic activity. The investigated substrate was a typical chernozem (black soil). Cellulolytic activity was studied by the application method across a regular grid of 7×15 points (21×45 m). The distance between the measurement points was 3 m. Soil heterogeneity determined by the measurement of soil penetration resistance using a hand penetrometer Eijkelkamp. Measurements of soil penetration resistance were fixed to a depth of 100 cm at intervals of 5 cm. Geostatistical analysis showed a high level of spatial dependence of soil cellulolytic activity. Significant correlations were obtained between the spatial distribution of cellulolytic activity and soil penetration resistance at different depths. The results reflect a significant correlation of soil conditions at different depths.

Key words: soil cellulolytic activity, soil heterogeneity, soil penetration resistance, geostatistics.

Introduction

The study of the spatial relationships of organisms with the environment they inhabit is becoming increasingly popular (Myšák et al., 2013; Kramarenko et al., 2014; Andrushevich, 2014; Andrushevich, Shtirts, 2014; Kunakh et al., 2018). On the one hand, the results of such studies make it possible to establish the spatial patterns of the formation of structures of living communities. On the other hand, they reveal so far unknown features of their environment. The soil is a component of the ecosystem and has a special status. It is both the result of and a necessary condition for the existence of life. The biologically inert nature of the soil and its hierarchical organization distinguish it from the inanimate components of the ecosystem and this confers on soil research its special character.

While studying soil penetration resistance across a regular grid, we found new elements in the soil structure (Zhukov, Zadorozhnaya, 2016). These soil morphological structures extend beyond the genetic horizons' limits and extend to the entire thickness of the soil. Their distribution in space is consistent with changes in environmental conditions and the plant community structure (Zadorozhnaya, Andrushevych, 2018; Zadorozhnaya et al., 2018). New soil elements have been found in all types of natural and technogenic soils that we studied. The dependence of their location on the spatial distribution of the other ecosystem components makes it possible to consider them elementary soil

bodies (Zhukov, Zadorozhnaya, 2015). The relationship of these morphological structures with soil organisms (soil biota) is not well understood.

Soil cellulolytic activity is an informatively valuable marker of its biological activity (Zhukov, Lyadskaya, 2009; Tryfanova et al., 2013). Cellulose is an important component of plant tissue. The rate of decomposition of cellulose affects the rate of decomposition of organic matter in general (Swift et al., 1979). The intensity of the cellulose destruction is negatively correlated with the amount of organic matter in the soil. A positive correlation is observed with pH, total phosphorus, iron, potassium, and extractive calcium. There is a significant correlation between the cellulose decomposition rate and the plant growth rate (Latter, Harrison, 1988).

The objective of this work was to clarify the relationship between the spatial location of the out-of-horizon soil morphological structures (ecological relations between the soil body structure) and the biological activity of black soil in terms of cellulolytic activity.

Material and methods

The test site is located in a steppe area adjacent to the southeastern slope of the Kamenistaya Gully (southern outskirts of the city of Dnipro, Ukraine), 48°38'67"N, 35°09'05"E. The material was collected in June 2016. The test sites are a regular grid of

Table 1. Statistical characteristics of the cellulolytic activity of black soil.

Cellulolytic activity	Average value	Median	Minimum	Maximum	Confidence interval	
					–95 %	+95 %
Initial data	1.27	1.32	0.51	2.01	1.20	1.33
Logit transformed data	0.77	0.76	0.63	0.91	0.76	0.78

Fig. 1. The distribution of the logit-transformed data values of the soil cellulolytic activity.

Notes: the boundaries of categories are plotted on the x axis, % (Category Boundary); the number of observations is plotted on the y axis, units.

Fig. 2. Variogram of spatial distribution of soil cellulolytic activity
Note: lag – the distance between pairs of sampling points (m) is plotted on the x axis, semivariation is plotted on the y axis. The points are experimental data, the solid line is a spherical model.

7×15 m. The distance between the sampling points was 3 m. Accordingly, the dimensions of each test site were 18×42 m.

The soil body structure was studied by indicators of soil penetration resistance. The soil penetration resistance was studied in the field environment to a depth of up to 50 at 5 cm intervals. A hand penetrometer Eijkelkamp was used in the study (Medvedev, 2009; Medina et al., 2012; Zhukov, Zadorozhnaya, 2016, 2017; Zadorozhnaya, 2018). The average error of the measurement results of the device is ± 8%. Soil penetration resistance was measured using a cone with a cross-section of 2 cm² in each section of the test site.

Soil cellulolytic activity was studied using an application method (Berg et al., 1975; Zhukov, Lyadskaya, 2009; Tryfanova et al., 2013). Pieces of paper of the same weight was used for the experiment. It was a substrate for the decomposition of cellulolytic enzymes. Circles of filter paper were placed in a polyethylene mesh (cell size – 1.5 mm) for the mechanical preservation of the material. The paper was inserted in the upper soil layer 0–10 cm. Samples were dried and weighed after 15 days. A measure of soil cellulolytic activity is decrease in the weight of the substrate during the exposure.

The obtained data was submitted to logit transformation. This is to ensure that the variable can be described by a normal distribution. Data is presented as part of the initial weight. The data takes a value from 0 to 1. For 1, the weight of the unused filter paper is taken.

Logit transformation was performed according to the formula:

$$Cell_{logit} = \ln \left(\frac{Cell}{1 - Cell} \right),$$

where $Cell_{logit}$ – log-transformed measure of soil cellulolytic activity, $Cell$ – measure of soil cellulolytic activity.

Data can be used in geostatistical models after logit transformation. Methods of descriptive statistics used in statistical calculations. Geostatistical data analysis was used to determine the spatial dependence level of soil indicators – soil penetration resistance and cellulolytic activity (Webster, Oliver, 2007; Valbuena Calderon et al., 2008; Shahbazi et al., 2013). The spatial dependence level (SDL, spatial dependence level, spatial relation) is calculated by the formula:

$$SDL = \frac{C_0}{C_0 + C_1} \times 100,$$

where C_0 – nugget-effect, C_1 – partial threshold.

Indicators C_0 , C_1 and radius of influence (R) are obtained on the basis of modeling variograms of indicators of spatial variability (Legendre, Fortin, 1989; Grunwald et al., 2001; Webster, Oliver, 2007).

The degree of relationship of spatial distribution of indicators of soil penetration resistance and cellulolytic activity was established using correlation analysis.

Table 2. Spatial variation parameters of black soil penetration resistance.

Distance from the surface, cm	Descriptive statistics		Geostatistics			
	$\bar{x} \pm SE$, MPa	CV, %	C_0	C_1	SDL, %	R, m
0–5	4.25 ± 0.15	35.65	0.31	2.18	12.45	9.6
5–10	4.96 ± 0.18	36.51	0.44	3.10	12.43	9.3
10–15	4.93 ± 0.18	38.14	0.62	3.00	17.13	9.7
15–20	5.08 ± 0.18	35.44	0.80	2.70	22.86	9.8
20–25	5.26 ± 0.15	29.44	0.75	2.60	22.39	8.2
25–30	5.17 ± 0.12	24.48	0.11	1.70	6.08	5.6
30–35	4.97 ± 0.11	22.20	0.17	1.19	12.50	7.5
35–40	4.85 ± 0.11	23.57	0.18	1.35	11.76	7.9
40–45	4.87 ± 0.11	22.35	0.20	1.10	15.38	8.8
45–50	5.14 ± 0.11	22.15	0.29	1.00	22.48	7.1
50–55	5.25 ± 0.12	23.23	0.24	1.18	16.90	5.7
55–60	5.47 ± 0.12	22.98	0.60	1.50	28.57	7.2
60–65	5.83 ± 0.13	22.21	0.55	1.20	31.43	6.9
65–70	6.03 ± 0.14	24.39	1.72	2.20	43.88	5.4
70–75	6.22 ± 0.15	24.89	1.58	2.14	42.47	6.3
75–80	6.29 ± 0.15	24.77	1.58	2.15	42.36	5.7
80–85	6.25 ± 0.15	23.91	1.12	2.25	33.23	7.1
85–90	6.20 ± 0.16	27.06	1.09	1.79	37.85	5.3
90–95	6.23 ± 0.17	27.26	0.76	2.20	25.68	5.8
95–100	6.43 ± 0.16	24.73	0.78	1.71	31.33	5.2
3MPa	4.52 ± 0.54	122.26	1.9	26.52	6.69	9.1

Notes: $\bar{x}$ – average values (MPa); SE – standard error; CV – variation coefficient (%); C_0 – nugget effect; C_1 – partial threshold; SDL – spatial dependence level (%); R – radius of influence (m).

Fig. 3. Spatial variability of soil cellulolytic activity (in logit-transformed form).

Results

Parametrical statistical assessment is based on the assumption of normal distribution of random variables. Estimates of the confidence interval for a variable may be outside the natural range from 0 to 1. Logit transformation allows us to obtain estimates

that correspond to the nature of the quantity being studied. Analysis of the data in Figure 1 indicates that the distribution of the studied quantity corresponds to the normal law. The Kolmogorov-Smirnov test confirms this conclusion ($d = 0.073$, $p < 0.2$). This allows us to use parametric statistical methods for further mathematical analysis (Table 1).

Fig. 4. Spatial distribution of values of soil penetration resistance in layers.

Fig. 5. Soil penetration resistance relief with a boundary criterion of 3 MPa.

The practical agreement of the mean and median values of cellulolytic activity also confirms the existence of a normal distribution law. The decomposition level of the substrate is in the range of 63–91%. 76–78% of the substrate decomposed in 95% of cases. A spherical model was chosen to describe the spatial variation of cellulolytic activity (Fig. 2). The nugget effect of the variogram (C_0) is 9.5, the partial threshold (C_1) is 41.43. The calculation of the index SDL – the level of spatial dependence is based on this data (*spatial dependence level* – $100 \cdot C_0 / (C_0 + C_1)$) (Cambardella et al, 1994; Diggle, Ribeiro, 2000). This indicator is 22.92%, which corresponds to a significant spatial dependence.

The spatial variability map of soil cellulolytic activity is based on the data obtained (Fig. 3).

Visual assessment of the map suggests the presence of localities with high cellulolytic activity. These sites are quite large. The radius of these sites is on average equal to 13.93 m. They form spatial structures. Cellulolytic activity values increase down the slope.

The soil penetration resistance increases with depth (Table 2). The variation coefficient is greatest in the upper layers of soil profile (0–25 cm). The spatial dependence level of the data is high in the upper half of the profile (0–55 cm) and has average values in the lower half.

Geostatistical data provide an opportunity to build maps of the spatial distribution of soil penetration resistance in layers (Fig. 4).

We can observe on the maps that the soil studied has a spatial structure. More solid areas are combined into spatial structures – elements of heterogeneity. These structures are found

Table 3. Correlation between the distribution of soil penetration resistance values and cellulolytic activity of the soil (N = 105).

Layers depth, cm	Correlation coefficient
0–5	-0.24 *
5–10	-0.46 *
10–15	-0.58 *
15–20	-0.49 *
20–25	-0.40 *
25–30	-0.26 *
30–35	-0.04
35–40	0.03
40–45	0.17
45–50	0.25 *
50–55	0.22 *
55–60	0.27 *
60–65	0.27 *
65–70	0.08
70–75	0.10
75–80	0.05
80–85	-0.04
85–90	-0.13
90–95	-0.21 *
95–100	-0.17
3MPa	-0.30 *

Note: * – significant correlations are noted at $p < 0.05$ (Marked correlations are significant at $p < 0.05$).

in less solid soil material. These elements of heterogeneity are similar to truncated cones in a three-dimensional image. Their radius ranges from 9.8 m to 5.2 m and decreases with depth (Table 2). The soil penetration resistance value of 3 MPa is found on average to a depth of 4.52 cm and is highly variable (CV = 122.26%). The outlines of spatial structures are visible on the three-dimensional image of the subsoil relief (Fig. 5).

The relationship between soil heterogeneity and cellulolytic activity of the soil was found during correlation analysis (Table 3).

A significant positive correlation is observed in layers 45–50 ... 60–65 cm below the surface. Cellulolytic activity has a negative correlation with soil penetration resistance in layers 0–5 ... 25–30, 90–95 cm. Also, negative correlation is observed with the spatial distribution of the soil penetration resistance value of 3 MPa.

Discussion

Soil heterogeneity is an inalienable property of the soil and is currently an object of active study (Salvador-Blanes et al., 2006; Soracco et al., 2010; Medvedev, 2013). Soil penetration resistance is an informative indicator of heterogeneity. Changes in penetration resistance correlate with a large number of soil indicators that are important for fertility. In addition, a large amount of data can be collected using a penetrometer in a relatively short period of time. These data are important for building geostatistical models. Our study found that the cellulolytic activity of black soil is closely related to its penetration resistance. The negative correlation between the studied parameters in the upper part of the soil profile indicates that cellulolytic activity is higher where the penetration resistance is less. This is completely logical because penetration resistance depends on the presence of organic matter in the soil (Grunwald et al., 2001; Medina et al., 2012). The higher the organic content, the lower the penetration resistance. At the same time, microorganisms feed on the organic matter in the soil, thereby decomposing it. Therefore, increase in the amount of organic matter increases their activity. However, a positive correlation was found between the penetration resistance indicator in the middle part of the soil profile and cellulolytic activity. Following our method, cellulose was placed in the soil layer 0–10 cm from the surface. The results reflect a significant correlation of soil conditions at different depths. We assume that this relationship is realized through the flows of soil moisture. The increasing soil penetration resistance at the depth of 45 to 65 cm creates a barrier to water and improves the conditions for the existence of microorganisms. As a result, in areas where the soil penetration resistance at this depth is higher, the soil has a higher biological activity. Our assumptions are confirmed by correlation with the position of the hardness barrier of 3 MPa. According to researchers, a penetration resistance of 3 MPa is the limit of penetration of the root systems of most plants. This position is disputed by other authors. The limit of penetration varies in the data of different authors from 0.8 to 5 MPa (Faechner et al., 2000; Bathke et al., 1992). However, the significant relationship established with cellulolytic activity of the soil confirms the importance of this indicator for the formation of ecological conditions of the soil. Similar results were obtained

by us earlier in a study of the cellulolytic activity of alluvial sod forest soil, which is formed on sandy sediments (Tryfanova et al., 2013). The cellulolytic activity of sandy soil is significantly lower than that of black soil. However, we observed an ecological relationship between the variation of soil penetration resistance at different depths and cellulolytic activity.

The results of our research demonstrate the great importance of spatial organization of the soil for the formation of its properties. A relationship of the soil structure with the spatial structure of other ecosystem components exists. As established, these ecosystem components are microorganisms and the plant community (Zadorozhnaya et al., 2018). The patterns revealed constitute a reason to describe the discovered morphological elements of the soil by the term soil bodies. These soil bodies are a form of existence of soil in the ecosystem and are characterized by the presence of direct ecological links with ecosystem components.

Conclusion

The flow of biological processes in the soil is closely related to its spatial heterogeneity on the basis of penetration resistance.

Black soil cellulolytic activity has a high level of spatial dependence. Sites of the same type are combined and form the spatial structure of the experimental area. The radius of sites with increased cellulolytic activity is on average equal to 13.93 m.

Indicators of soil penetration resistance have a high spatial dependence from the surface to a depth of 55 cm. The average level of spatial dependence is characteristic of the lower half of the soil profile (60–100 cm from the surface). The greatest variability of penetration resistance indicators was recorded in the upper layers of the soil profile (0–25 cm deep). Geostatistical modeling allows one to find three-dimensional structures of spatial heterogeneity. These elements of heterogeneity have a radius of 9.8 to 5.2 m. Their size decreases with depth.

Indicators of cellulolytic activity demonstrate a significant negative relationship with increased penetration resistance in layers 0–5 ... 25–30, 90–95 cm from the surface. Sites of soil with high penetration resistance in layers 45–50 ... 60–65 cm from the surface are characterized by high cellulolytic activity of the black soil surface layer.

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