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Int. Agrophys., *2012, 26, 117-128*
doi: 10.2478/v10247-012-0018-6

Morphometrical structure evaluation of long-term manured Ukrainian chernozem

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Abstract. There was performed an image analysis of the structure of Ukrainian chernozem, which (I) by standard crop rotation was fertilized for 78 years with farm yard manure and (II) by continuous cultivation of sugar beet was not organically fertilized. For the both soils the largest differences were stated in the values of morphometrical parameters related to the soil solid phase element cross-sections. The differences in the parameters for pore cross-sections were much smaller. The soil I was characterized on average with larger macroporosity, larger relative and absolute number of solid phase element cross-sections, and larger relative length of border line between pore and solid phase element cross-sections than the soil II. For the both pedons the pore and solid phase element cross-sections were in general randomly oriented in the soil body. Due to the kneading the pore cross-sections in the superficial layer of the soil after monoculture of sugar beet were oriented horizontally. The soil structure in the corresponding layers of both pedons was to a high degree dissimilar. The largest differences in the arrangement of the soil solid phase and void space occurred in the upper layers.

Keywords: chernozem, farm yard manure, structure, image analysis, morphometry

INTRODUCTION

Soil science has accumulated a vast body of data on the chemical (Blagodatskaya *et al*., 2007; Karbozova-Saljnikova *et al*., 2004; Russow *et al*., 2008; Sleutel *et al*., 2006), some physical properties (Korolev, 2007) and evolution of chernozems (Chendev *et al.*, 2010; Eckmeier *et al.*, 2007) and crop yield achieved on chernozems (Berzsenyi *et al.*, 2000; Kunzová and Hejcman, 2009; Nadezhkina *et al.*, 2008). Still, there is a need of the acquisition of new data on the chernozem structure with use of modern techniques. The role of soil structure in the creation of the favourable water-air regime in soil of medium and heavy granulometric composition is well known. The control of plant development, use of fertilizers and precipitation moisture is possible with creation of the optimum ratio (mixture) of various aggregates in the soil plough layer. The best for cereal crops would be the layer in the upper part of which predominate coarse (directly contacting with seeds) aggregates, and in the lower – smaller ones (Medvedev, 1996; Ţopa *et al.*, 2009).

It is universally acknowledged, that chernozems have an ideal and exemplary aggregate structure. The aim of the study was to verify this opinion. Consequently, there was performed a quantitative characterization of the structure of Ukrainian chernozem, which was fertilized for many years with farm yard manure (I) and was not supplied with organic fertilizers at all (II). The evaluation was made *via* image analysis of sections through impregnated blocks of undisturbed soil, which allowed for the assessment of number, size, shape, and orientation of both soil solid phase elements (including aggregates) as well as pores, which also are valuable indicators of the structural state of soil (Skvortsova and Sanzharova, 2007; Skvortsova and Utkaeva, 2008).

MATERIALS AND METHODS

The research was accomplished in the scientific cooperation with A.N. Sokolovskiy Research Institute of Soil Science and Agrochemistry in Kharkiv. The chernozem is located in the forest-steppe nearby the Mironovsky Research Institute of Selection and Wheat Seed-farming (Kiev district) in Mironovka (49º40´N, 31º00´E; Ukrainian Upland).

In the experimental station there were conducted several long term stationary field surveys. In the present paper two of them will be characterized. The first experiment (I) was founded in 1912 and since then every year by standard

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*Corresponding author's e-mail: maja.bryk@up.lublin.pl crop rotation farm yard manure (FYM) had been applied at the rate of 16 t ha^{-1}. Consequently, between 1912 and 1966 in the 5-field crop rotation up to 870 t ha^{-1} of FYM was added, and in the 7-field crop rotation – up to 610 t ha^{-1}. The humus content in the succeeding layers after 54 years of FYM application was: 4.06 (0-20 cm), 3.31 (20-40 cm), 2.64 (40-60 cm), 1.81 (60-80 cm), and 1.24 g (100 $g)^{-1}$ (80-100 cm) (Kudzin and Getmanec, 1968). The 10-year crop rotation on 5 fields consisted of the treatments and crops: black fallow – winter wheat – sugar beet – maize – oats – winter wheat – sugar beet – silage maize – winter wheat – barley (EuroSOMNET, 2001). The second field experiment (II) started in 1929, and was organized as a continuous cultivation of sugar beet (monoculture) without any inputs of farm yard manure.

In 1990, after harvest of winter wheat and sugar beet, for experiment I and II, respectively, for the morphological description of soil structure, the samples of undisturbed structure were taken from the two pedons, representing each variant of the experiment. Two soil blocks were sampled in the vertical plane from 5 layers of each profile: 0-8, 10-18, 20-28, 30-38, and 40-48 cm into metal boxes measuring 9×8×4 cm. Subsequently they were dried at the room temperature, impregnated with polyester resin and after hardening cut in the vertical plane into 1 cm plates. For each soil and each layer four plates were obtained from which one representative opaque block was chosen for the following study. Then the plates were polished to obtain opaque block faces suitable for image analysis. Their faces were scanned at the 600×600 dpi resolution. The digitized photographs in 256 shades of grey were subjected to image analysis using a computer program Aphelion (ADCIS SA, AAI Inc., 1997). First, the images were segmented with a threshold operator. In that manner, soil pore space (black colour) and soil solid phase (white colour) were separated from the images. The resolution used by a scanner and the applied morphological parameters limited the minimum size of the object *ie* a cross-section of pore or solid phase element to 42.3 μm.

On the basis of the whole binary (black and white) image, cross-sectional areas (A_i, mm^2) of pores and solid phase elements were measured. Number (N) and perimeters (L_i, mm) of objects were determined however for cross-sections, whose gravity centres were included within the protection frame, that is a centrally situated rectangle enclosing 80% of the binary image area. The following parameters were calculated for each sample:

- A_{AP} – relative area of pore cross- sections (macroporosity, $\phi > 42.3$ µm; mm^2 mm^{-2});
- A_{AS} – relative area of solid phase element cross-sections ($A_{AS} = 1 - A_{AP}$, mm^2 mm^{-2});
- N_S and N_P – absolute number of cross-sections of solid phase elements and pores, respectively;
- N_{AS} and N_{AP} – relative number of solid phase elements and pores cross-sections: average number of objects per 1 cm^2 of the protection frame (cm^{-2});
- A_{NS} and A_{NP} – average area of aggregate and pore cross-sections (mm^2);
- L_A – relative length of objects: length of border line between pore and solid phase element cross-sections per unit area of the protection frame (mm mm^{-2}).

Equivalent diameters of soil solid phase element (d_S, mm) and pore (d_P, mm) cross-sections were calculated from the formula for a circle area on the basis of object cross-sectional area. The cross-sections were categorized into 734 size classes, according to their equivalent diameter in the range from 0 to 93.218 mm at every 0.127 mm (equivalent to 3 pixels in an image). The summarized cross-sectional area in each class of sizes was divided by A_{AS} (for solid phase) or A_{AP} (for pore space), consequently the obtained normalized and dimensionless values were in the 0-1 range. Afterwards the graphs were drawn for the function of integral normalized relative pore or solid phase area versus the equivalent diameter of a pore or solid phase element cross-section. The plots allowed for straightforward comparison of the object size distributions for each layer and experiment (Bryk, 2010). The distributions were compared via the nonparametric λ Kolmogorov-Smirnov compatibility test at the significance level $\alpha = 0.05$.

The mean intercept length across solid λ_S (mm) and pores λ_P (mm) (Bryk, 2000) was calculated on the basis of the equations: $\lambda_S = \pi(A_{AS}/L_A)$ and $\lambda_P = \pi(A_{AP}/L_A)$. The two local morphometrical parameters were good estimates of the average size of solid phase element and pore cross-section, respectively.

The elongation factor, ELG, was calculated for solid phase element and pore cross-sections according to the equation: $ELG_i = (a_i–b_i)/(a_i+b_i)$, where a_i and b_i were, respectively, major and minor axis of the best ellipse fit of an object. In view of the difficulty in shape classification of small objects, for the shape analysis the cross-sections with the area of at least 100 pix^2 were chosen, which corresponded to 0.179 mm^2. The elongation index ELG is close to 0 for uniform shapes (squares, circles, circles with a hole) and approaches 1 for a narrow and long forms. Consequently, the following groups of cross-sections were defined according to the value of the elongation index: circular (ELG 0-0.140), elliptical (ELG 0.141-0.500) and elongated ones ($ELG > 0.501$). The orientation of elliptical and elongated pore and solid phase element cross-sections was then measured. The circular objects were not subjected to the analysis since they had not a main axis of orientation (Kołodziej *et al.*, 2004). The orientation was evaluated on the basis of the angle created between the longer side of the minimum rectangle bounding an object and the horizontal axis of the image. The angles increased counterclockwise in the range from 0° (horizontal direction) through 90° (vertical direction) to 180° at every 15°. The values of the angles were grouped in the 12 left-hand closed intervals: [0;15), [15;30) *etc*. The results were presented as circular histograms – rose diagrams constructed using an equal-area frequency scale, with the sector area proportional to the class frequency. Due to the fact that the orientation data for the pore or solid phase element cross-sections were of the lineational (not directional) type, the obtained distributions were in effect semi-circular. Consequently the graphs were drawn symmetrically also for the other half of the circle *ie* for the angles 180-360° (Bryk *et al.*, 2005). The rose diagrams were plotted with use of the EZ-ROSE 1.0 program (Baas, 2000). The statistical analysis of lineational data was made via the parametric Rayleigh test at the significance level $\alpha = 0.05$. The test compared the distribution of a particular population with a circular-normal distribution of von Mises type. The statistics calculated included the orientation of the mean vector (M, °) and a confidence sector for the vector mean (d, °) (Batschelet, 1981; Mann *et al.*, 2003). The distributions were compared additionally with each other via the nonparametric Kolmogorov-Smirnov statistical test at the significance level $\alpha = 0.05$.

RESULTS AND DISCUSSION

In the soil after harvesting of winter wheat, which by a standard crop rotation was for 78 years fertilized with farm yard manure (FYM) – experiment I – macroporosity was quite diverse (Table 1) and fluctuated from 0.092 (30-38 cm) to 0.368 $\text{mm}^2\ \text{mm}^{-2}$ (10-18 cm). Superficial layers of the soil (0-8 and 10-18 cm, Fig. 1a, b) had the most developed boundary between pores and solid phase, which was demonstrated by a high value of L_A.

The structure of the 0-18 cm layer, which to a high extent could be described as an aggregate one, was undoubtedly the effect of a proper agrotechnique. Aggregates in the silty soils usually have a propensity to disintegrate under influence of water. In the studied soil, which granulometric composition was clayey silt, the aggregates owed their existence to a high quantity of humus due to regular supplies of FYM.

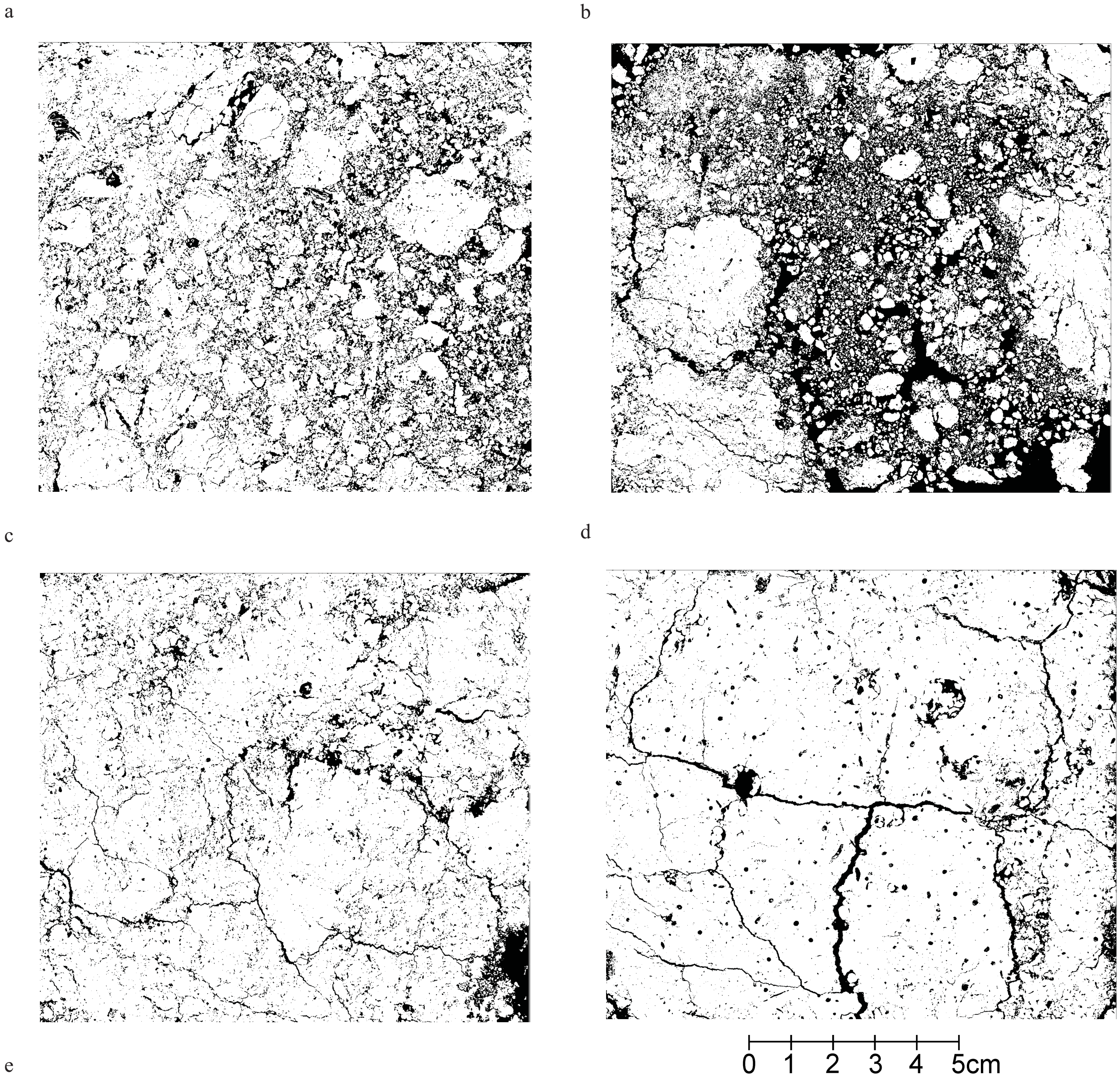
The both upper layers were characterized with large number of soil solid phase element cross-sections in comparison to the next two layers. The soil in the superficial layer was however more compacted than in the deeper one. It was proved by the lower than in the 10-18 cm layer macroporosity, lower absolute and relative number of solid phase element cross-sections and their larger average size (Table 1).

The soil in the 40-48 cm (Fig. 1e) and 0-8 cm layers revealed similar values of morphometric parameters (Table 1). The presence of discrete aggregates in the lower part of soil profile was the effect of soil fauna activity. The soil in this layer was out of the range of working parts of tillage implements, consequently the soil structure in the layer represented essentially the natural structure of a typical chernozem. In contrast to that observation the soil in the 20-28 and 30-38 cm (Fig. 1c, d) layers was characterized with a quite low macroporosity (Table 1). The number of soil solid phase elements in these layers was 3, and even nearly 13 times lower than in the neighbouring layers. Low values of N_{AS} parameter (8-10 cm^{-2}) and high of A_{NS} (*ca.* 11-15 mm^2) and λ_S (*ca.* 1.5-2.5 mm) proved that the solid phase was quite compacted, that is only several large aggregates were present. Cumulated effect of long-term kneading, caused by the action of heavy agricultural machines, was observed in this part of the soil profile, giving the soil some features of a plough-pan.

The integral curves of normalized solid phase relative area vs. equivalent diameter of a solid phase element cross-section (Fig. 2) confirmed the above observations. It is worth to mention at this point that the performed Kolmogorov-Smirnov compatibility test revealed statistically valid differences for the size distributions in each possible pair of soil layers. It was undoubtedly related to the large sizes of samples *ie* large values of N_S. Nonetheless, the solid phase element size distributions in the layers 0-8, 20-28, 30-38, and 40-48 cm were quite comparable. The soil layers were characterized with continuous solid phase; the integral curves were terminated with a visible step related to a large object *ie* the part of soil solid phase, which was formed as a result of the consolidation of aggregates. In the four layers the proportion of area of small aggregates in the relative area of solid phase was minimal and consequently hardly noticeable in the graph (Fig. 2). The solid phase elements of the equivalent

Table 1. Values of morphometrical parameters for pore and solid phase element cross-sections of Ukrainian chernozem. Experiment I – standard crop rotation and fertilization with 16 t ha^{-1} FYM since 1912

Layer (cm)	A_{AP} ($\text{mm}^2\ \text{mm}^{-2}$)	L_A (mm mm^{-2})	N_S	N_P	N_{AS} (cm^{-2})	N_{AP} (cm^{-2})	A_{NS} (mm^2)	A_{NP} (mm^2)	λ_S (mm)	λ_P (mm)
0-8	0.199	3.26	1 459	12 510	27	234	3.65	0.09	0.77	0.23
10-18	0.368	3.55	6 303	7 753	113	139	0.68	0.31	0.56	0.35
20-28	0.113	1.98	554	10 315	10	194	10.67	0.05	1.41	0.25
30-38	0.092	1.16	453	5 017	8	87	14.45	0.09	2.47	0.35
40-48	0.191	2.31	1 577	9 715	30	185	3.35	0.11	1.10	0.30
0-48 mean	0.193	2.45	2 069	9 062	38	168	6.56	0.13	1.26	0.30



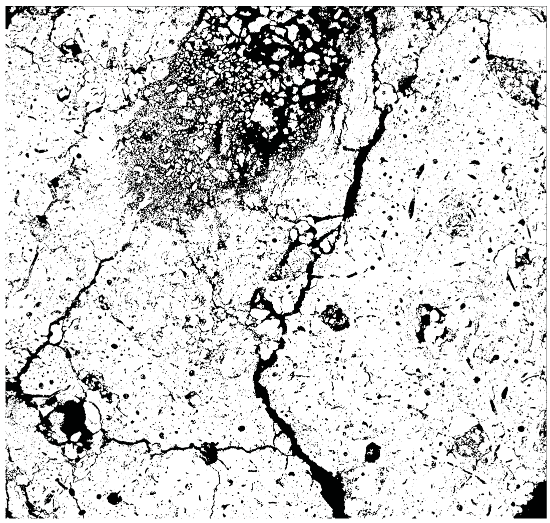


Fig. 1. Structure of Ukrainian chernozem. Experiment I – standard crop rotation and fertilization with 16 t ha^{-1} FYM since 1912. Figures in the 60% of the original size; black colour – pores; white colour – solid phase. Layers: a – 0-8, b – 10-18, c – 20-28, d – 30-38, e – 40-48 cm.

diameter below 0.48 mm *ie* the ones of cross-sectional area less than 100 pix^2 (0.179 mm^2) were however the most numerous group of cross-sections. In the successive layers they consisted: 96.1 (0-8 cm); 83.9 (10-18 cm), 94.4 (20-28 cm), 96.2 (30-38 cm) and 86.9% (40-48 cm) of the total number of solid phase element cross-sections. On the other hand, in the 10-18 cm layer the discrete aggregates were more abundant than in the other layers. It was demonstrated by the stepwise increase of the integral curve (Fig. 2).

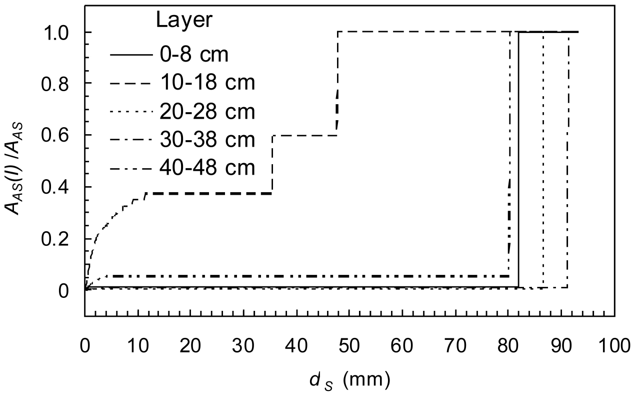


Fig. 2. Integral curves of normalized solid phase relative area *vs.* equivalent diameter of a solid phase element cross-section of Ukrainian chernozem. Experiment I.

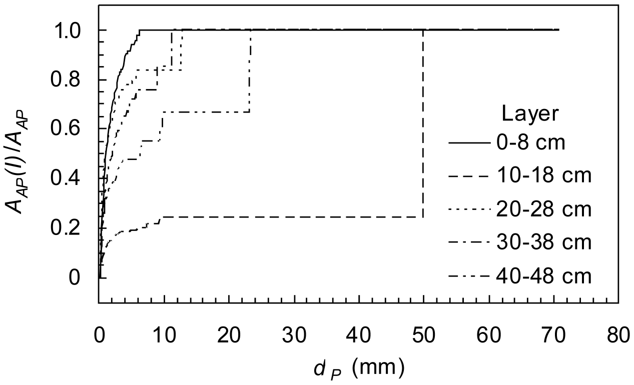


Fig. 3. Integral curves of normalized macroporosity *vs.* equivalent diameter of a pore cross-section of Ukrainian chernozem. Experiment I.

The arrangement of soil pore space corresponded with the complementary solid space. In the layers of the high disintegration of soil solid phase the pores built continuous space, whereas in the layers of greater density and consolidation, the discrete pores were more or less regularly located in the soil body. The observed differences were confirmed by the values of morphometric parameters (Table 1) and the shapes of integral curves of normalized macroporosity *vs.* equivalent diameter of a pore cross-section (Fig. 3).

The absolute and relative number of pore cross-sections in each layer was very high (N_P, N_{AP}, Table 1). The highest values of the parameters were noted in the 0-8 cm layer, while the lowest ones – in the 30-38 cm layer. The objects of the equivalent diameter below 0.48 mm *ie* the ones of cross-sectional area less than 100 pix^2 (0.179 mm^2) prevailed in the samples. In the successive layers the pore cross-sections of this size consisted: 93.0 (0-8 cm); 95.8 (10-18 cm); 96.4 (20-28 cm); 94.4 30-38 cm); 95.7% (40-48 cm) of the total number of pores. The smallest pores were quite uniformly situated in the soil body. Between the developed aggregates some irregular and larger pores were present. The average size of pore cross-sections expressed by the parameter λ_P was not widespread and comprised in the range from 0.23 to 0.35 mm. The parameter A_{NP} showed, however, that the pores of the largest average cross-sectional area (0.31 mm^2) were present in the 10-18 cm layer. The layer was characterized with the highest macroporosity and at the same time – one of the smallest number of pore cross-sections. The pores were interconnected and built continuous void space in which distinct aggregates were located. In the 0-8, 30-38, and 40-48 cm layers the values of A_{NP} parameter were virtually equal, reaching 0.09-0.11 mm^2. The pores of the minimum average cross-section (0.05 mm^2) were present in the 20-28 cm layer.

The integral curves of normalized macroporosity vs. equivalent diameter of a pore cross-section (Fig. 3) revealed the visible in Figs 1a-1e differences in the character of the void space through the soil pedon. The variation for the pore size distributions in each possible pair of soil layers was confirmed via the Kolmogorov-Smirnov statistical test. For the 10-18 cm layer the last vertical part of the curve was moved towards the right side of the graph and the remaining part of the curve was quite flat. The shape of the curve resulted from the minor proportion of small pore cross-sections and the presence of continuous void space, occupying the most part of the soil sample. The distribution curve for the superficial layer (0-8 cm) was situated in the other end of the graph. The soil in this layer was characterized with abundance of pore cross-sections of diameters less than 6 mm. The pore size distributions for the 20-28 and 30-38 cm layers were very similar, and the likeness of structures was also evident in the Figs 1c, d. In the deepest layer (40-48 cm) the high percentage of macroporosity came from a zoogenic channel situated in the upper section of the sample. This pore cross-section was visible in the graph (Fig. 3) as the last stage of the curve. Taking into account the characteristics for solid phase and pore space (Table 1 and Figs 2, 3) it was stated that the soil structure in the 10-18 cm layer was noticeably different from the structures for the remaining layers of the soil pedon in the experiment I.

The configuration of soil porous system dominates the soil hydraulic properties. The quantitative information on structure is therefore indispensable to predict transport in soils, which generally cannot be considered to be macroscopically homogeneous (Kodešová *et al.*, 2009; Vogel *et al.*, 2006). It is commonly recognized that both the size and connectivity of soil pores play major roles in the flow characteristics of water and the transportation of solutes through soil. In our study we concluded that the manuring treatment improved chernozem aggregation and consequently we could expect enhancement of water transmission properties. It is generally acknowledged that addition of organic matter improves soil properties such as aggregation, water-holding capacity, hydraulic conductivity, bulk density, the degree of compaction, fertility and resistance to water and wind erosion. In the upper chernozem layers which were characterized with aggregate structure, the fast movement of water ('preferential flow') would occur through the large inter-aggregate pores and would be accompanied with much slower water flow through the system of touching aggregates. The soil below the plough layer still preserved sufficient continuity of earthworm burrows and interaggregate macropores (such as fractures) and therefore guaranteed unproblematic water transport. Moreover, earthworm burrows could play a dominant role at the solute transition between the upper soil horizon and the subsoil. The stable aggregate soil structure is characterized with favourable soil hydraulic properties: high porosity and soil water retention; higher fraction of the large capillary pores, which are important for water flow and various substances transport in soils; lower fraction of gravitational pores, which may enlarge contaminant leakage into the subsurface layers and consequently into the groundwater (Kodešová *et al.*, 2011).

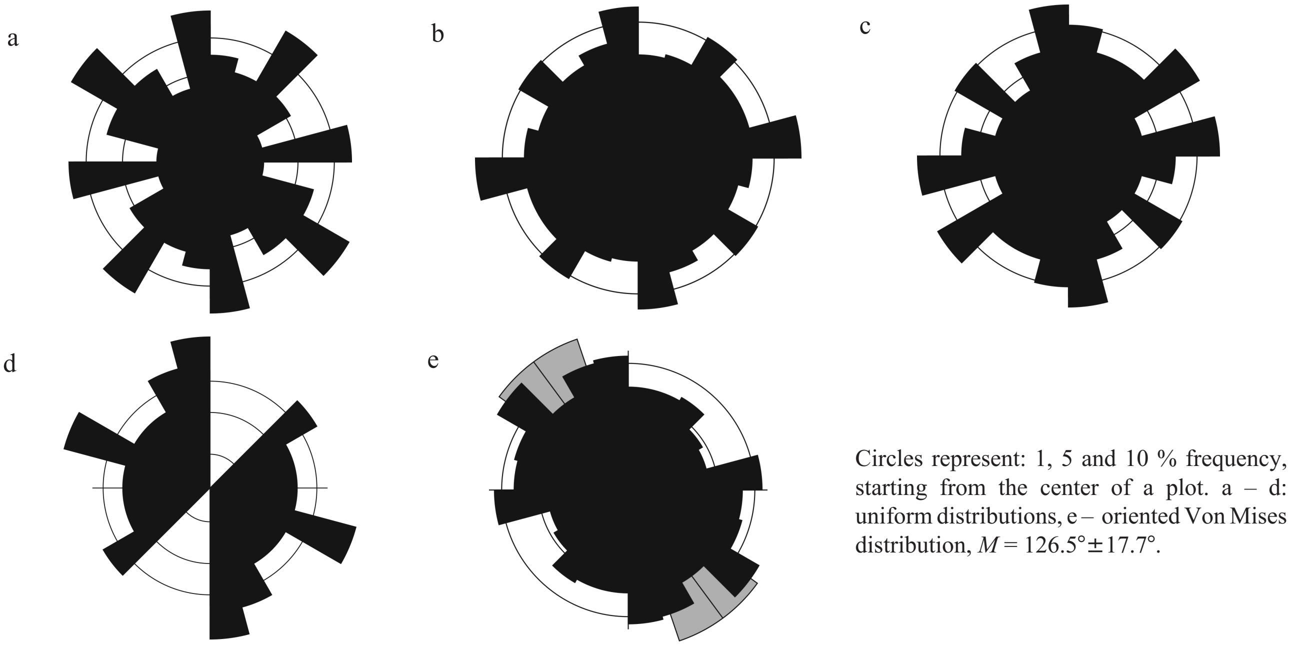
The analysis of elongation factor, *ELG*, revealed that the round solid phase element cross-sections consisted 4.8-11.8% of their total number N_{S100}, whereas the proportion of the round pore cross-sections was in the range 3.0-11.4% of their total number N_{P100} (Table 2). The average percentage of the elliptical and elongated solid phase cross-sections was virtually equal and reached 46.3-46.9%. In the studied soil there were also *ca.* 30% of the elliptical pore cross-sections and *ca.* 65% of the elongated ones. After the preliminary evaluation of the elongation factor, the orientations of elliptical and elongated solid phase element and pore cross-sections were measured. The relevant rose diagrams (circular histograms) were presented in Figs 4, 5. For the orientation distributions following the circular-normal frequency distribution, known as the von Mises distribution, the black line represented the mean vector orientation, and the corresponding confidence sector for the mean vector orientation was depicted with a grey sector. Both the pore cross-sections as well as the solid phase element cross-sections in the entire pedon were randomly oriented, in consequence in majority of the layers the orientation distributions were uniform. In the 40-48 cm layer, however, the solid phase element cross-sections were diagonally oriented (circular-normal von Mises distribution, $M = 126.5° \pm 17.7°$), and in the 10-18 cm layer the pore cross-sections were situated virtually horizontally (circular-normal von Mises distribution, $M = 9.5° \pm 18.8°$).

In the upper layers (0-8 and 10-18 cm) of the chernozem which was not fertilized with FYM at all, and which was for more than 60 years under continuous cultivation of sugar beet (experiment II), the macroporosity was lower than in the corresponding layers of organically fertilized soil (Table 3, Fig. 6a, b). The cultivation of sugar beet led to consolidation of the soil around conical roots of the plants, and their growth and harvesting caused removal of substantial amounts of organic matter from the soil, which could reduce aggregation (Blair *et al.*, 2006; Haynes and Beare, 1995). The unfavourable phenomena intensified in particular during long-term cultivation of sugar beet without crop-rotation, when there were no supplies of organic fertilizers. The regeneration of valuable aggregate structure could not occur between consecutive vegetation seasons. The innate high erodibility and water vulnerability of aggregates in silt-type soil strengthened by insufficient supply of organic matter caused considerable kneading of the soil.

Bezuglova and Yudina (2006) stated that in long-term cultivated chernozems the well-pronounced plough-pan clearly separates the humus layer into the plough and subsoil layers. Moreover, the long-term agricultural use of chernozems worsens their agrophysical properties: the plough and subsoil layers are compacted, the percentage of agronomically valuable particles decreases, and coarse clods appear in the upper horizons. The water stability of soil aggregates decreases by four-five times in comparison with virgin soils. Thus, agricultural use leads to changes in the agrophysical soil properties, which affects humification and mineralization of soil organic matter.

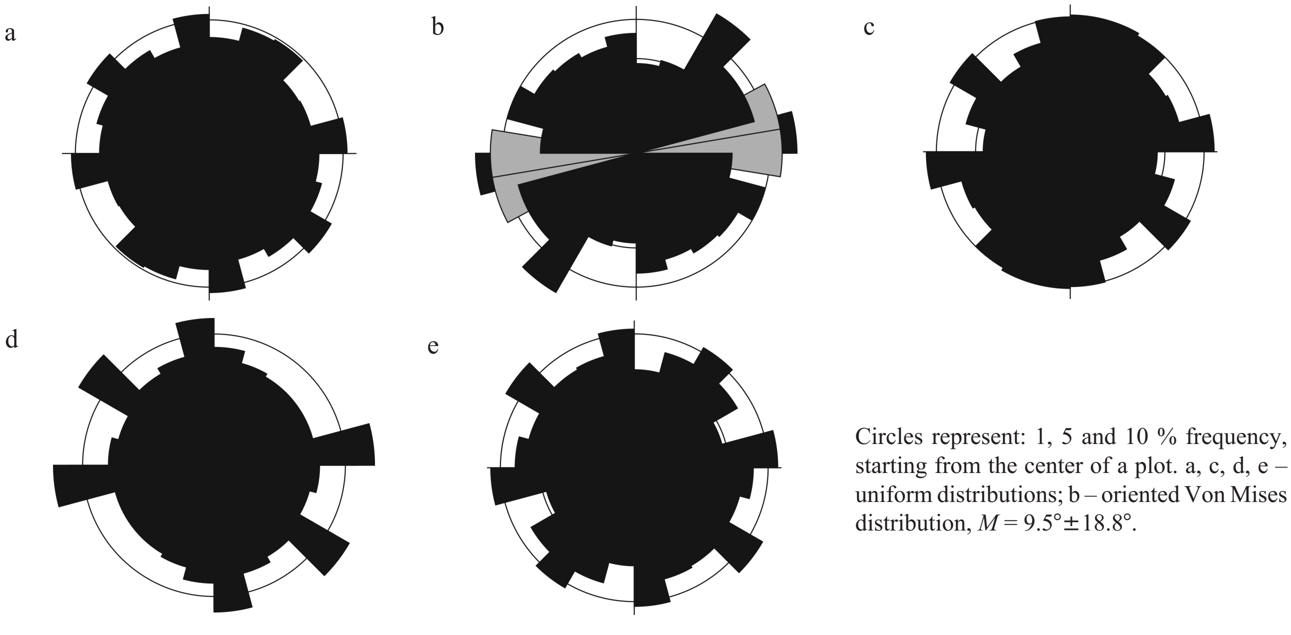
Table 2. Number of solid phase element (N_{S100}) and pore (N_{P100}) cross-sections of area > 100 pix^2 (0.179 mm^2); quantity (qty) and percentages of round, elliptical, and elongated cross-sections for Ukrainian chernozem. Experiment I

Layer (cm)	Solid phase element cross-sections > 100 pix^2							Pore cross-sections > 100 pix^2						
	N_{S100}	round		elliptical		elongate		N_{P100}	round		elliptical		elongate	
		qty	%	qty	%	qty	%		qty	%	qty	%	qty	%
0-8	57	3	5.2	27	47.4	27	47.4	876	26	3.0	293	33.4	557	63.6
10-18	1 012	56	5.5	489	48.3	467	46.2	324	12	3.7	101	31.2	211	65.1
20-28	31	2	6.5	17	54.8	12	38.7	370	15	4.1	90	24.3	265	71.6
30-38	17	2	11.8	6	35.3	9	52.9	280	32	11.4	86	30.7	162	57.9
40-48	207	10	4.8	95	45.9	102	49.3	420	28	6.7	119	28.3	273	65.0
0-48 mean	265	15	6.8	127	46.3	123	46.9	454	23	5.8	138	29.6	293	64.6



Circles represent: 1, 5 and 10 % frequency, starting from the center of a plot. a – d: uniform distributions, e – oriented Von Mises distribution, $M = 126.5° \pm 17.7°$.

Fig. 4. Orientation of elliptical and elongated soil solid phase element cross-sections of Ukrainian chernozem. Experiment I. Explanations as in Fig. 1.



Circles represent: 1, 5 and 10 % frequency, starting from the center of a plot. a, c, d, e – uniform distributions; b – oriented Von Mises distribution, $M = 9.5° \pm 18.8°$.

Fig. 5. Orientation of elliptical and elongated pore cross-sections of Ukrainian chernozem. Experiment I. Explanations as in Fig. 1.

The current study confirmed the aforementioned observations. The macroporosities in both sublayers of the plough layer (0-18 cm) were lower than in the deeper layers which contrasted to the situation observed in the chernozem fertilized with FYM. The 20-28 and 30-38 cm layers (Fig. 6c, d) were characterized with comparable structures and similar values of morphometric parameters to the analogous regions of the pedon in experiment I, although they revealed slightly higher macroporosity. A quite low soil macroporosity was noted, on the other hand, in the lowest, 40-48 cm layer (Fig. 6e). The morphometric analysis (Table 3) confirmed moreover that the soil structure in the whole pedon was to a higher extent uniform in contrast to the soil structure in experiment I. Visible likeness and homogenizing of solid phase arrangement in the succeeding layers of the soil was manifested in the graphs of solid phase element cross-section size distribution (Fig. 7). The obtained integral curves were of the almost identical shape of a reversed letter *L*. The soil solid phase was consolidated and few minor aggregates were present inside larger pores.

Table 3. Values of morphometrical parameters for pore and solid phase element cross-sections of Ukrainian chernozem. Experiment II – monoculture of sugar beet without FYM fertilization since 1929

Layer (cm)	A_{AP} (mm^2 mm^{-2})	L_A (mm mm^{-2})	N_S	N_P	N_{AS} (cm^{-2})	N_{AP} (cm^{-2})	A_{NS} (mm^2)	A_{NP} (mm^2)	λ_S (mm)	λ_P (mm)
0-8	0.076	1.63	224	12 212	4	207	30.47	0.03	1.78	0.19
10-18	0.122	1.69	388	9 670	7	168	16.09	0.07	1.63	0.27
20-28	0.161	1.76	523	6 470	9	117	11.13	0.15	1.49	0.37
30-38	0.165	1.32	317	8 021	5	139	18.81	0.13	1.98	0.48
40-48	0.105	1.84	548	10 710	9	185	11.80	0.06	1.53	0.23
0-48 mean	0.126	1.65	400	9 417	7	163	17.66	0.09	1.68	0.31

The compatibility Kolmogorov-Smirnov test revealed that the solid phase element size distributions for analogous layers of the soil in the experiment I and II were statistically different. The substantial differences were noted primarily for the plough layer, 0-18 cm. In this part of the horizon the most visible, often unfavourable reorganization of soil structure occurred, related to kneading and consolidation of soil body. The last vertical branch of the integral curve of normalized solid phase relative area *vs*. equivalent diameter of a solid phase element cross-section for 0-8 cm layer moved to the right side of graph. The curve for the 10-18 cm layer lost its stepwise character and the last vertical part also moved to the right side. The shapes of the curves resulted from the occurrence in the soil of a compacted region of the size practically equal to the size of the entire sample. As a result, in relation to the experiment I, the values of parameter L_A were in both two upper layers by half the size lower. Additionally, the number of soil solid phase elements decreased and consequently the average size of solid phase element cross-sections increased: A_{NS} was 30.47 and 16.09 mm^2, whereas λ_S was 1.78 and 1.63 mm, for 0-8 and 10-18 cm, respectively.

Similarly obvious alteration was observed within the void space, particularly in the 10-18 cm layer (Fig. 8). After long-term cultivation of sugar beet without organic fertilization, the soil in this layer became very dense, and the previously joined pores became disconnected. As a consequence, a large quantity of tiny pores (less than *ca*. 7 mm in diameter) developed in the soil, and the integral curve of pore cross-section size distribution obtained a completely different shape. The observed differences in pore size distributions of the two corresponding layers of the soil in the experiment I and II were confirmed by the λ Kolmogorov-Smirnov compatibility test. Equally strong modification of the pore space arrangement did not occurred, however, in the superficial 0-8 cm layer.

High consolidation, in respect to the soil from the experiment I, was detected also in 40-48 cm layer. Corresponding layers in both pedons were characterized with similar structure, in the experiment II, however, there were not detected zoogenic channels, which were responsible for visible loosening of the soil in the experiment I. The observation was reflected in the graphs of pore cross-section size distribution for the analogous layers of the two pedons (Figs 3 and 8). The curve for the soil in the experiment II rapidly increased in the diameter range 0-6 mm, in contrast to the corresponding curve for the soil in the experiment I.

The arrangement of the soil solid phase and void space in the 20-28 cm layer in both experiments was quite comparable (Figs 3 and 8). The more apparent dissimilarity was stated, on the other hand, in the 30-38 cm layer. The soil after the monoculture of sugar beet was characterized with a greater value of macroporosity, and, moreover, with the presence of larger pores than the analogous soil from the experiment I. The pore diameters in 30-38 cm layer in the soil in the experiment I did not reached 11 mm, and in the corresponding part of the soil in the experiment II they exceeded 26 mm.

The average pore cross-section A_{NP} increased gradually down the soil profile from 0.03 (0-8 cm) to *ca*. 0.15 (30-38 cm). Similar trend was observed for the value of λ_P parameter, which increased from 0.19 (0-8 cm) to 0.48 mm (30-38 cm). The deepest 40-48 cm layer was similar to the 10-18 cm layer in respect to its structure, and particularly – the arrangement and size distribution of pore cross-sections (Figs 6b, e, 7, 8, Table 3). The negative consequences of sugar beet monoculture without organic fertilization showed not only in the decrease of humus content and consolidation of the plough layer, but also in limiting the activity of soil macrofauna which is responsible for the soil loosening in the deeper layers.

The objects of the equivalent diameter below 0.48 mm *ie* the ones of cross-sectional area less than 100 pix^2 (0.179 mm^2) prevailed in the samples. In the successive layers the solid phase elements of this size consisted: 98.2 (0-8 cm); 97.7 (10-18 cm); 90.4 (20-28 cm); 89.6 (30-38 cm); 96.2% (40-48 cm) and analogous pores consisted: 97.6 (0-8 cm); 94.7 (10-18 cm); 92.0 (20-28 cm); 97.0 (30-38 cm); 95.8% (40-48 cm) of the total number of corresponding structural elements.

Upon compaction (densification) of soil the macropores were the most significantly reduced in size, which can have a profound effect on both saturated and unsaturated water transmission. The water flow rates would decrease by the

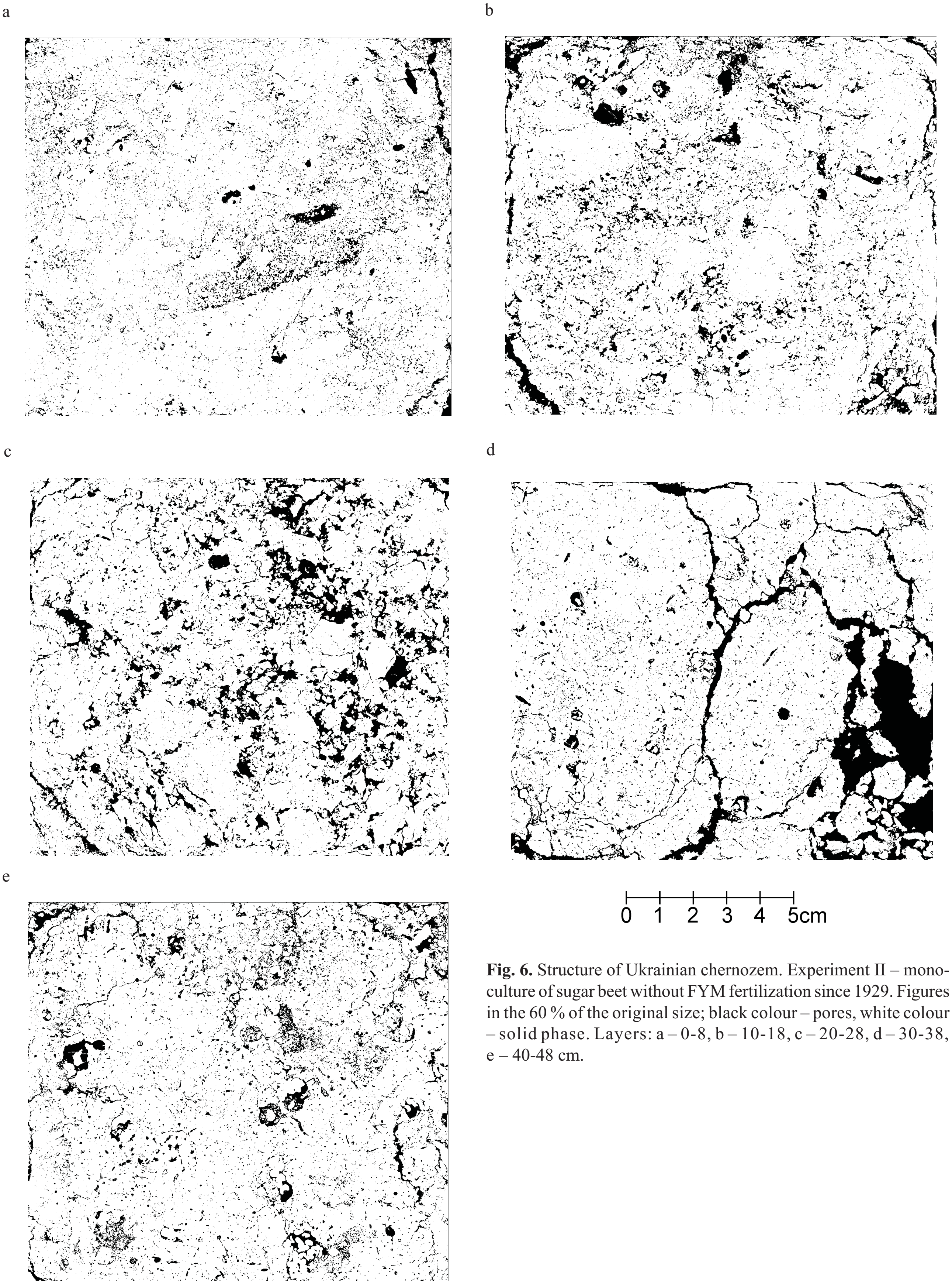


Fig. 6. Structure of Ukrainian chernozem. Experiment II – monoculture of sugar beet without FYM fertilization since 1929. Figures in the 60 % of the original size; black colour – pores, white colour – solid phase. Layers: a – 0-8, b – 10-18, c – 20-28, d – 30-38, e – 40-48 cm.

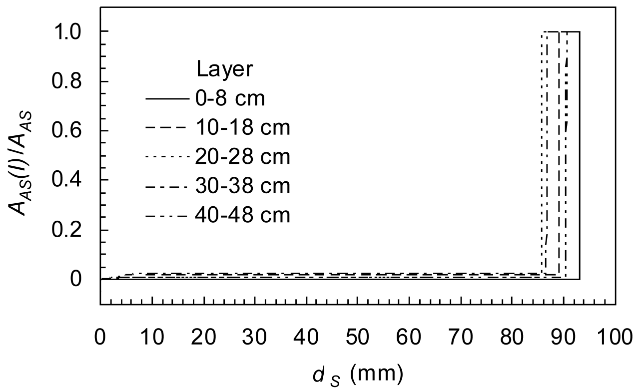


Fig. 7. Integral curves of normalized solid phase relative area *vs.* equivalent diameter of a solid phase element cross-section of Ukrainian chernozem. Experiment II.

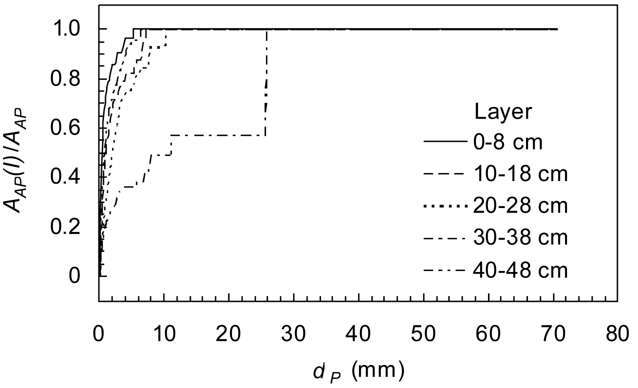


Fig. 8. Integral curves of normalized macroporosity *vs.* equivalent diameter of a pore cross-section of Ukrainian chernozem. Experiment II.

Table 4. Number of solid phase element (N_{S100}) and pore (N_{P100}) cross-sections of area > 100 pix^2 (0.179 mm^2). Experiment II. Explanations as in Table 2

Layer (cm)	Solid phase element cross-sections > 100 pix^2							Pore cross-sections > 100 pix^2						
	N_{S100}	round		elliptical		elongate		N_{P100}	round		elliptical		elongate	
		qty	%	qty	%	qty	%		qty	%	qty	%	qty	%
0-8	4	1	25.0	2	50.0	1	25.0	295	10	3.4	85	28.8	200	67.8
10-18	9	2	22.2	3	33.3	4	44.5	517	10	1.9	157	30.4	350	67.7
20-28	50	7	14.0	22	44.0	21	42.0	518	13	2.5	156	30.1	349	67.4
30-38	33	1	3.0	19	57.6	13	39.4	237	8	3.4	76	32.1	153	64.5
40-48	21	1	4.8	11	52.4	9	42.8	448	18	4.0	138	30.8	292	65.2
0-48 mean	23	2	13.8	11	47.5	10	38.7	403	12	3.0	122	30.5	269	66.5

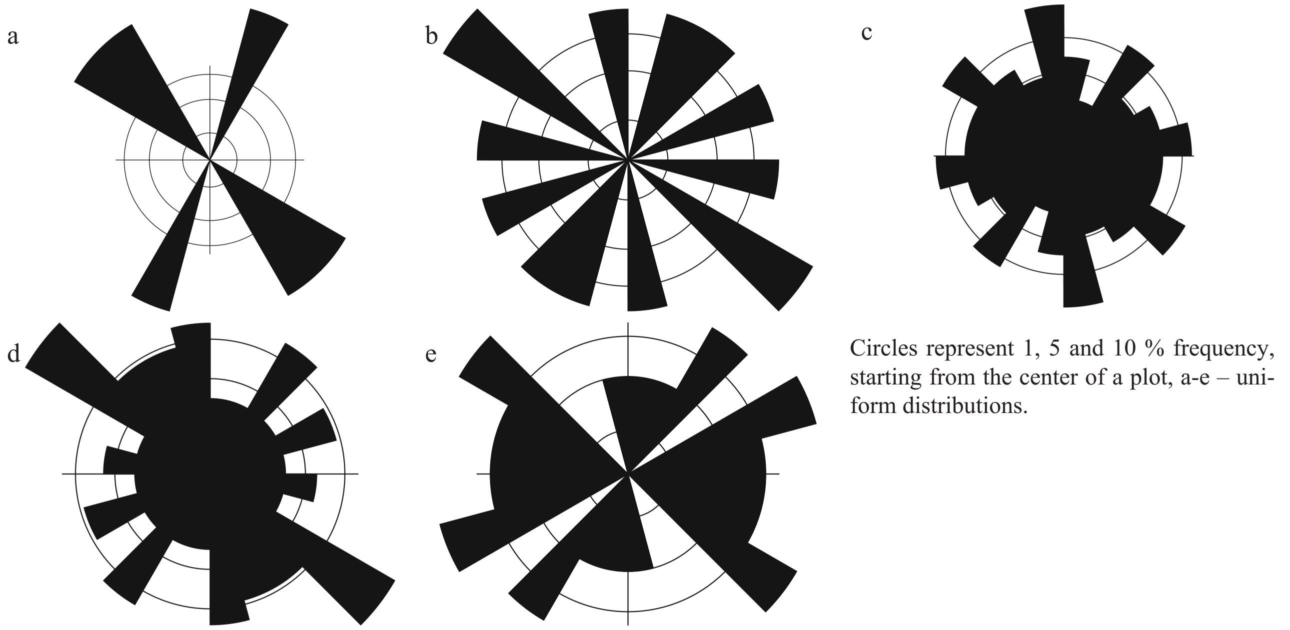
absence of gravitational pores and a low fraction of large capillary pores. Intense agricultural use increases bulk density and reduces hydraulic conductivity (saturated and unsaturated) and plant available water (reduced field capacity). This is mainly due to soil compaction by using heavy machines and by a reduction in macrofaunal activity (Bormann and Klaassen, 2008). The phenomena could be pronounced stronger in a silty soil which aggregate structure is not stabilized by systematic supplies of organic matter.

In the chernozem which was not fertilized with FYM at all by a monoculture of sugar beet (experiment II) the round solid phase element cross-sections consisted 3.0-25.0% of their total number N_{S100}, whereas the proportion of the round pore cross-sections was in the range 1.9-4.0% of their total number N_{P100} (Table 4). The average percentage of the elliptical and elongated solid phase cross-sections was in the range 33.3-57.6 and 25.0-44.5%, respectively. In the studied soil there were also *ca.* 30% of the elliptical pore cross-sections and *ca.* 66% of the elongated ones.

The tested soil in most cases showed an isotropic distribution of elliptical and elongated solid phase element and pore cross-sections (Figs 9, 10). The observed anisotropy of pore orientation in the upper layers (0-8 and 10-18 cm) resulted mainly from the compaction of soil. In the two layers the pore cross-sections were situated horizontally, at an angle of 176.2°±13.8° and 6.3°±14.2°, respectively. The λ Kolmogorov-Smirnov compatibility test revealed, that the pore cross-section orientation distributions in the superficial layers of soil in experiment I and II were different. The pore cross-sections in the soil after monoculture of sugar beet were to a higher degree oriented horizontally in contrast to soil in experiment I.

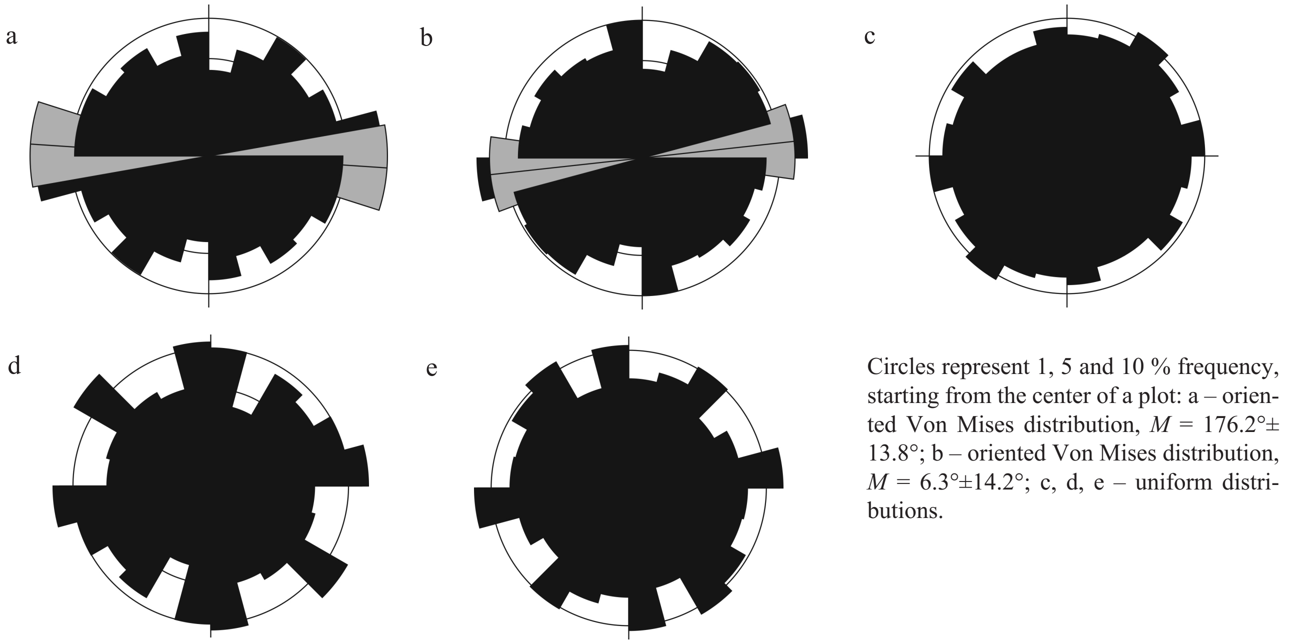
CONCLUSIONS

1. The image analysis enabled to obtain many valuable morphometric parameters and size distributions of pore and solid phase element cross-sections of a high resolution (734



Circles represent 1, 5 and 10 % frequency, starting from the center of a plot, a-e – uniform distributions.

Fig. 9. Orientation of elliptical and elongated soil solid phase element cross-sections of Ukrainian chernozem. Experiment II. Explanations as in Fig. 6.



Circles represent 1, 5 and 10 % frequency, starting from the center of a plot: a – oriented Von Mises distribution, *M* = 176.2°± 13.8°; b – oriented Von Mises distribution, *M* = 6.3°±14.2°; c, d, e – uniform distributions.

Fig. 10. Orientation of elliptical and elongated pore cross-sections of Ukrainian chernozem. Experiment II. Explanations as in Fig. 6.

size classes every 0.127 mm). It allowed for the detailed characterization of the chernozem structure in relation to the used cultivation and fertilization modes.

2. The largest differences were stated for the values of morphometric parameters related to the soil solid phase element cross-sections. The soil, which for 78 years was fertilized with FYM, had more than 5 times larger number of soil aggregates and their average sizes expressed by A_{NS} were almost 3 times lower than for the soil after monoculture of sugar beet and without supplies of FYM. For the both soils the differences in the parameters for pore cross-sections were much smaller.

3. The soil under standard crop rotation and fertilized for 78 years with FYM was characterized on average with larger macroporosity, larger relative and absolute number of solid phase element cross-sections, and larger relative length of border line between pore and solid phase element cross-sections than the soil after monoculture of sugar beet and not fertilized with FYM at all. These parameters revealed less significant compaction of the soil supplied with FYM.

4. The pore and solid phase element cross-sections > 0.179 mm^2 were in general randomly oriented in the soil body. Due to the kneading the pore cross-sections in the superficial 0-8 cm layer of the soil after monoculture of sugar beet were oriented horizontally. The orientation of pore cross-sections of the analogous layer of the soil supplied with FYM was, on the other hand, isotropic.

5. The soil structure in the corresponding layers of the soil in both experiments was to a high degree dissimilar. The largest differences in the arrangement of the soil solid phase and void space occurred in the upper layers (0-8 and 10-18 cm).

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