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Int. Agrophys., 2013, 27, 81-87
doi: 10.2478/v10247-012-0071-1

Long-term organic fertilization effect on chernozem structure

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Received March 7, 2011; accepted April 28, 2011

A b s t r a c t. The objective of the study was to examine the structure of typical Ukrainian chernozem developed on loess, which (I) had been fertilized by standard crop rotation since 1912 with farm yard manure at the rate of 16 t ha^{-1} and (II) had not been fertilized with farm yard manure by sugar beet monoculture since 1929. After harvest of winter wheat and sugar beet, the samples of undisturbed structure were taken from 5 layers of both profiles: 0-8, 10-18, 20-28, 30-38, and 40-48 cm. The morphological analysis of the structure of the investigated chernozem revealed that the most visible differences between the soil structures of the two pedons occurred in their superficial layers. The 0-18 cm layer of the soil in the experiment I had an aggregate structure, whereas analogous layer of the soil in experiment II was much more compacted. Below about 30 cm from the ground level both pedons had very similar structure. For the soil in the experiment I an appropriate crop rotation and regular supplies of organic matter allowed for preservation of a favourable structure even in the upper layers – in contrast to the soil in the experiment II.

K e y w o r d s: soil structure, morphology, Ukraine, Haplic Chernozem, humus

INTRODUCTION

Chernozems were of a special importance in the history of soil science, since they were an object of general interest due to their exceptional fertility. For that reason chernozems were better analysed and examined than other soils. Moreover, the representative features of chernozems are relatively evident, so even with the basic knowledge in soil science it is quite easy to distinguish these soils. Boundaries of chernozem areas are clearly discernible and their territories are limited to selected geographical zones in contrast to the territories of other soils. In Europe, in the plains of the Ukraine, Belarus and Russia, chernozems and podzoluvisols zones form the largest continuous area of soils predominantly suitable for agriculture (Rabbinge and van Diepen, 2000).

Since Dokuchaev investigations in Russia, chernozems were defined as steppe soils, with their pedogenesis dominated by the soil-forming factors of dry continental climate and steppe vegetation, with carbonaceous parent material, mainly loess, and intense bioturbation shown by krotovinas (animal burrows) as other prerequisites (Driessen *et al.*, 2001; IUSS Working Group WRB, 2007). Due to the activity of steppe vegetation roots, soil organisms, the presence of calcium ions, and the ability of humic acids to coagulation, chernozems are characterized with a favourable aggregate structure.

In the Ukraine, current soil productivity is the result of rich genetic development, degradation, and years of productivity. Fertile soils have degraded throughout the years by insufficient conservation, the absence of a clear land use policy, and incomplete improvement and maintenance programs. More than 60% of the Ukraine soils are deep, fertile chernozems and more than 75% of them is under cultivation. Since 1980s, humus levels of Ukrainian soils have dropped by an average of 400 kg ha^{-1} (Medvedev, 2004). According to Mnatsakanian (1992) the main reason of loss of humus layer in the Ukrainian steppe is soil erosion: when in the end of 19. century Russian pedologist Dokuchaev investigated Ukrainian chernozems, the most fertile of them contained 11-12% of humus. Unfortunately, in the end of 20. century the most rich Ukrainian soils contained 5-6% of humus, and its average amount was estimated at 3.2%. Mikhailova *et al.* (2000) reported that organic carbon in continuously cropped fields was equal to 62% of natural grassland fields on

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Russian chernozem. Similar results obtained Kadono *et al.* (2008). Some models showed that for climatic conditions characteristic for Ukrainian forest-steppe region it is possible only to decelerate soil organic carbon loss or preserve current levels (Smith *et al.*, 2007; Svetlitchnyi, 2009). Kharytonov *et al.* (2004) observed that erosion on soil physical and chemical properties in the chernozem of the central Ukrainian steppe generated unfavourable conditions in the studied 1 m-thick horizon.

Devyatova and Shcherbakov (2006) stated that independently of the method of soil cultivation without the application of fertilizers (primarily or organic ones), the humus content decreased gradually. As organic and organomineral fertilizers were applied, the population of microorganisms participating in the synthesis of humus substances increased. In order to maintain the high biochemical activity of soils and their biogenic properties, the combined application of organic and mineral fertilizers is recommended for producing stable yields of crops. In their research, the systematic application of manure accelerated the decomposition of the nonspecific organic compounds and the synthesis of humus substances.

As stated above, chernozems have been extensively studied because of their great agricultural significance (Altermann *et al.*, 2005; Dostovalova, 2009; Filonenko and Filonenko, 2008; Franko *et al.*, 2007). One of such experiments was included in the EuroSOMNET (Smith *et al.*, 2002) database, concerning long-term field research that investigated dynamics of soil organic matter and the influence of diverse factors on yields. The experiment No. 57 in the EuroSOMNET was conducted in Ukraine (Kiev district) in the Mironovsky Research Institute of Selection and Wheat Seed-farming and provided information of yield and physico-chemical parameters of the soil. The analysis of soil structure could enhance the above-mentioned information, supplying data for aggregates and porosity. This enables the deepening of interpretation and understanding of processes taking place in soil, and gives comprehensive knowledge about soil. Consequently, the objective of the present study was to examine the status of the structure of typical Ukrainian chernozem developed on loess, which (I) have been fertilized for 78 years with farm yard manure and (II) have not been fertilized with farm yard manure at all.

MATERIALS AND METHODS

The soil is located in the forest-steppe nearby the Mironovsky Research Institute of Selection and Wheat Seed-farming (Kiev district). The experimental station is placed in Mironovka, in the flat territory of right bank of Dnieper river within the Ukrainian Upland (49º40´N, 31º00´E). The region is located in the temperate continental climate zone, of mean annual temperature in the range of 6.6-7.2ºC. The average annual precipitation is 550 mm, from which 75% occurs between April and October, and the sum over years ranges from 392 to 925 mm.

Parent rock of the soils in the investigated area is loess, characterized with columnar structure, low porosity, high capillary rise and high proportion of carbonates. The carbonates form pseudomycelia and firm nodules at the 60-70 cm depth. Groundwater level is situated at about 50-60 m and has no effect on pedogenesis of the soils. The soils of the investigated area are in Russian classification categorized as typical deep chernozems, slightly, moderately, or strongly leached (Classification of Russian Soils, 2010; Lebedeva *et al.*, 2008). They are characterized with low water stability, which diminishes their water permeability. The main feature of the investigated pedons is a very thick humic horizon, reaching approximately to 125-130 cm from the ground level. The humus content in the arable layer (0-25 cm) is about 4.3 g 100 g^{-1}, which in the 25-30 cm layer decreases to 3 g 100 g^{-1}. The base saturation in the arable layer reaches 25 cmol(+) kg^{-1}, and 87% originates from Ca^{2+} ions (Kudzin and Suchobrus, 1966).

The granulometric composition of the arable layer of the soil in the investigated area was on average: 12.3 (fine and very fine sand: 0.25-0.05 mm); 55.7 (coarse and partially fine silt: 0.05-0.01 mm); 4.1 (fine silt: 0.01-0.005 mm); 5.3 (partially fine silt and clay: 0.005-0.001 mm) and 22.6 g 100 g^{-1} (clay: < 0.001 mm) . The percentage of the 1-0.25 mm fraction was negligible. The soil was classified as silty clay.

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 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). 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.

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 both 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. After drying at the room temperature they were impregnated with polyester resin and after hardening cut in the vertical plane into 1 cm plates. Then, with use of powders and papers of decreasing granulation, they were polished to obtain opaque block faces suitable for image analysis. For each soil and each layer four plates were obtained from which one representative opaque block was chosen for the following study. The faces of selected plates were scanned at the 600×600 dpi resolution, and as a result photographs in 256 shades of grey were obtained, which were then utilized for precise morphological description of the structure of two selected pedons of the investigated chernozem with help of image analysis. The results of the morphometrical study for both experiments were presented by Bryk *et al.*(2012).

RESULTS AND DISCUSSION

The size, shape and stability of aggregates, which arise as an effect of miscellaneous environment factors, are subject to change. The stability of aggregates is greatly influenced by soil organic matter. The addition of organic materials to the soil, such as cereal straw, farm yard manure, manures from intensive livestock industries or sewage sludge has the potential to improve soil fertility, nutrient cycling and soil structure (Balashov *et al.*, 2010; Swift, 2001).

The results of our study confirm the above-mentioned observations. The 0-8 cm layer of the chernozem feritilized yearly with FYM (experiment I, Fig. 1A) represented favourable aggregate structure (FitzPatrick, 1984; Jongerius and Rutherford, 1979). The most valuable *ie* zoogenic aggregates dominated and they were uniformly situated in the soil body. The existence of aggregates of that kind was undoubtedly related to regular supplies of organic matter in the form of FYM. The enlarged sections (Fig. 1B) clearly demonstrated completely developed aggregate structure in the 0-8 cm layer. Complete subspherical and spherical peds were uniformly situated in the continuous pore space. In the soil moderately sized (0.2-2 mm) and large (2-10 mm) aggregates dominated. The surface of aggregates was smooth. The observed structure was hierarchical and the inner structure of macroaggregates was classified as the semi-aggregate one. That model type of structure was present also in the 10-18 cm layer, however the soil at this depth was even looser than in the superficial layer (Fig. 2A, B). Additionally, the second layer was characterized with more heterogeneous arrangement of solid phase than the upper one. In the 10-18 cm layer very loose regions were adjacent to more compact zones. The increase in aggregation as a result of long-term FYM application was also observed by Blair *et al.* (2006) for a Haplic Phaeozem. Carbon compounds in soil organic matter provide some of the major soil constituents involved in binding soil into aggregates, particularly in lower clay content soils, and stability of soil aggregates increases with increased levels of soil organic matter. When manure is applied to the soil, the labile forms can result in short-term increases in aggregation, while the more resistant components of the manure can have a longer term effect.

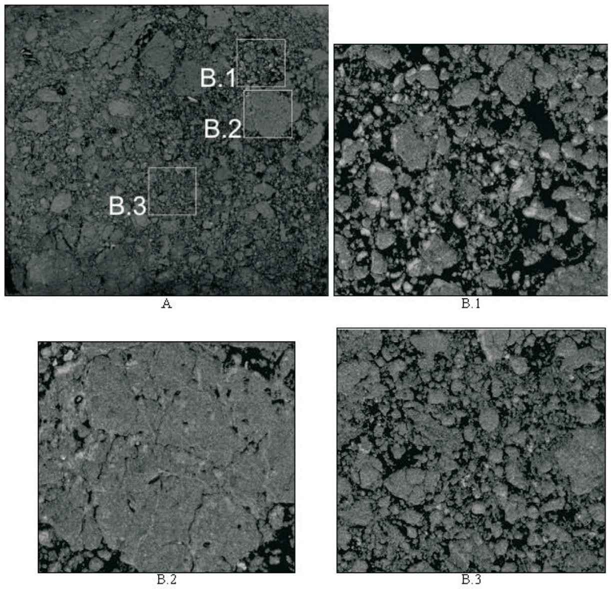

Fig. 1. Structure of the 0-8 cm layer of Ukrainian Haplic Chernozem. Standard crop rotation and fertilization with 16 t ha^{-1} FYM since 1912. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale, black colour – pores.

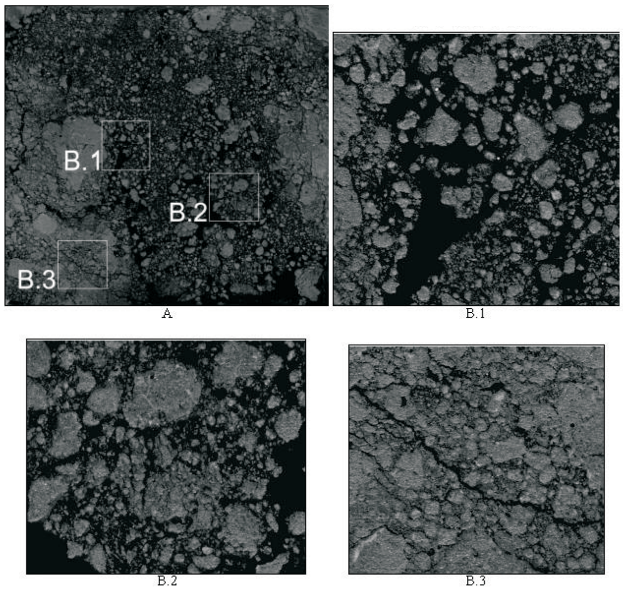

Fig. 2. Structure of the 10-18 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 1.

Below approximately 20 cm the soil lost its aggregate structure, which became porous and fissury-jointed one. That kind of structure was visible in the whole 20-28 cm layer (Fig. 3A). Pores – fissures and channels – were interconnected building a complex system, but no loose aggregates were visible. In the photographs of enlarged sections (Fig. 3B) small regions of aggregate structure could be observed, nonetheless the void space surrounding the aggregates was more limited than in the upper layers. Moreover, the semi-aggregate structure was quite frequent. In the 30-38 cm layer similar fissury-jointed and porous structure was present (Fig. 4A). The soil body was cut by wide fissures, which were interconnected creating relatively regular system. Emerging soil blocks had porous interior. The enlarged photographs (Fig. 4B) quite evidently illustrated the disappearance of the aggregate structure. The biogenic channels played an important role in the compacted soil mass. In the chernozems abundant in soil mesofauna, even in the regions of higher soil density, the effects of the mesofauna activity are visible. There are large biogenic channels and chambers, frequently filled with spherical peds. At the 40-48 cm depth (Fig. 5A, B) among the fissures wide zoogenic channels were visible, reflecting intense activity of soil fauna. Burrows made by soil animals were filled with loosely arranged aggregates – vermiforms. The soil body was characterized with the abundance of pores.

The basic factor which favoured a stable aggregate structure of the studied chernozem, particularly in the 0-18 cm layer, was the regular supply of organic matter. In chernozems the main binding agent is humus with the prevalence of humic acids, which built stable complexes with mineral fraction of soil. The humic acids play a fundamental role both in micro- as well as in macroaggregation (Travnikova *et al.*, 2006). The humate component of soil organic matter includes compounds strongly cementing the mineral colloids so that water cannot disperse the aggregates even at the complete saturation of the soil with sodium.

Insufficient organic fertilization, resulting from the erroneous belief that in such humus-abundant soils as chernozems the organic supplementation in unnecessary, leads to negative balance of soil organic matter. Long-term agricultural utilization of soil without proper crop rotation effects a decrease of amount of soil humus due to predominance of decomposition of organic matter processes and its mineralization. Humus losses reduce soil fertility and reduce the soil ability to withstand the physical impacts. As a result, soils gradually lose their valuable structure, their water, air, heat, and nutrition regimes are irreversibly deteriorated, and the soil erosion is accelerated (Balyuk *et al.*, 2008).

The results of the experiment II support the aforementioned findings. Many years without organic fertilization and continuous cultivation of sugar beet caused unfavourable modification of chernozem structure in the 0-8 cm layer (Fig. 6A). In the upper layer the soil was compacted, and in the relatively dense soil body there were discernible boundaries of unporous aggregates measuring approximately 1-2 cm. They neighboured slightly looser zones, characterized with fine-aggregate structure. Large pores were practically absent. Completely developed aggregates were visible in the enlarged sections (Fig. 6B), nevertheless they were smaller (0.2-1 mm) and, what is more important, situated much more densely than in the superficial layer of the soil in the experiment I. Similar, however to some extent looser, arrangement of solid material was observed in the 10-18 cm layer (Fig. 7A, B). The loosening caused by soil fauna was particularly visible in the lower part of the layer, while in the upper part larger pores – channels – emerged.

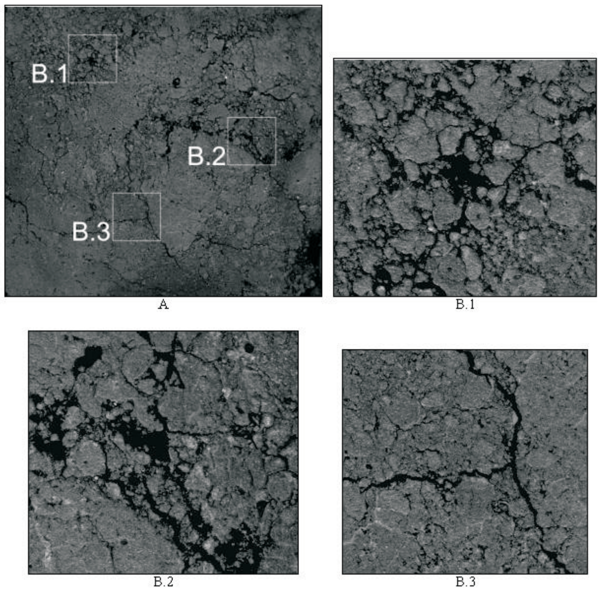

Fig. 3. Structure of the 20-28 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 1.

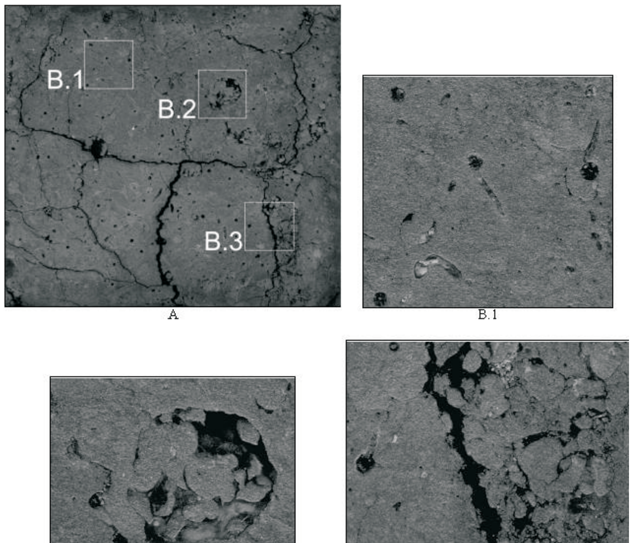

Fig. 4. Structure of the 30-38 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 1.

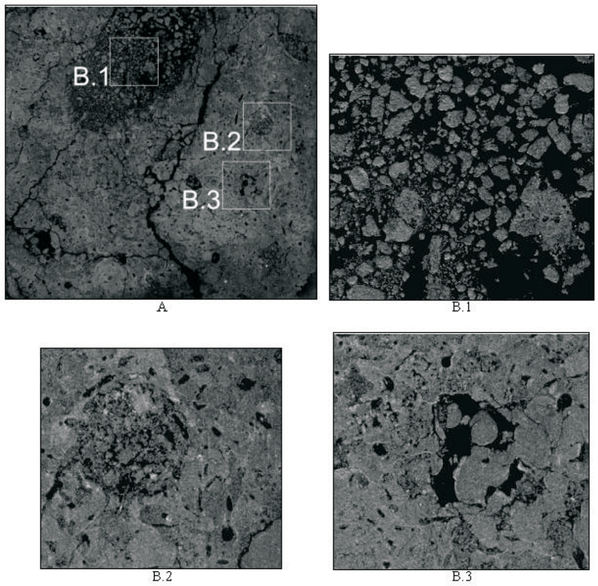

Fig. 5. Structure of the 40-48 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 1.

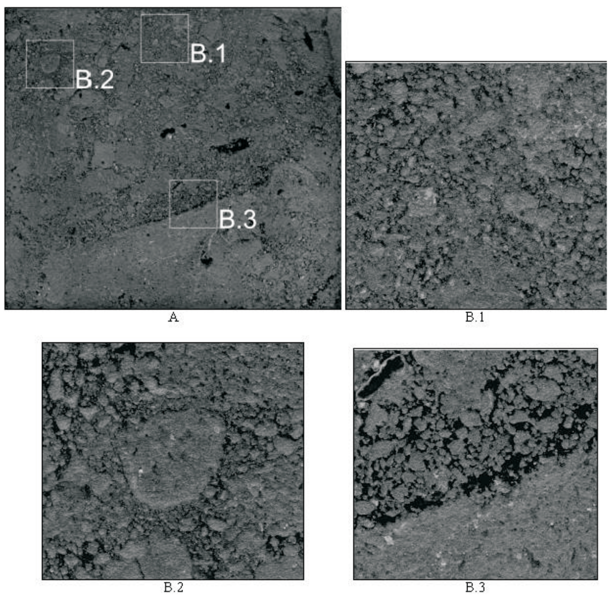

Fig. 6. Structure of the 0-8 cm layer of Ukrainian Haplic Chernozem. Monoculture of sugar beet without organic fertilization since 1929. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Black colour – pores.

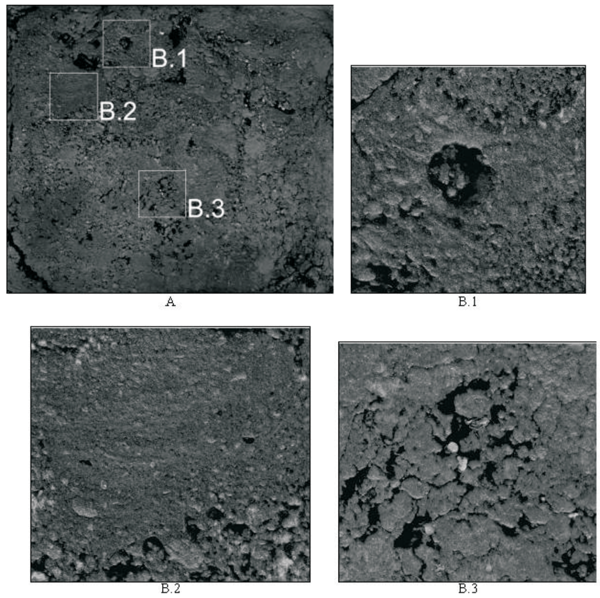

Fig. 7. Structure of the 10-18 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 6.

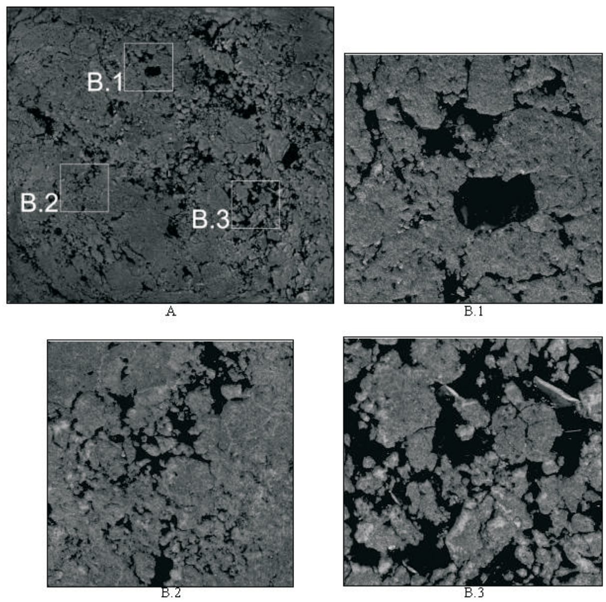

Fig. 8. Structure of the 20-28 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 6.

Comparable results obtained Balashov and Buchkina (2011). They stated that the 75 year agricultural management of the clayey loam Haplic Chernozem caused a decrease in content of clay, soil organic matter and microbial biomass carbon in comparison to fallow land and soil cultivated for 45 years. In consequence, the total amount of water-stable aggregates in the 0-20 cm Haplic Chernozem layer was reduced and the distribution of water-stable aggregate fractions altered – the quantity of the 1.0-7.0 mm fraction decreased, whereas the quantity of the 0.25-0.5 mm fraction increased.

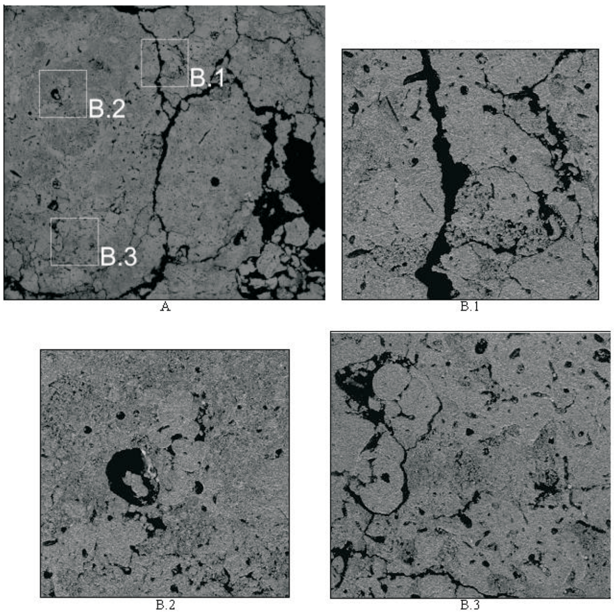

Fig. 9. Structure of the 30-38 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 6.

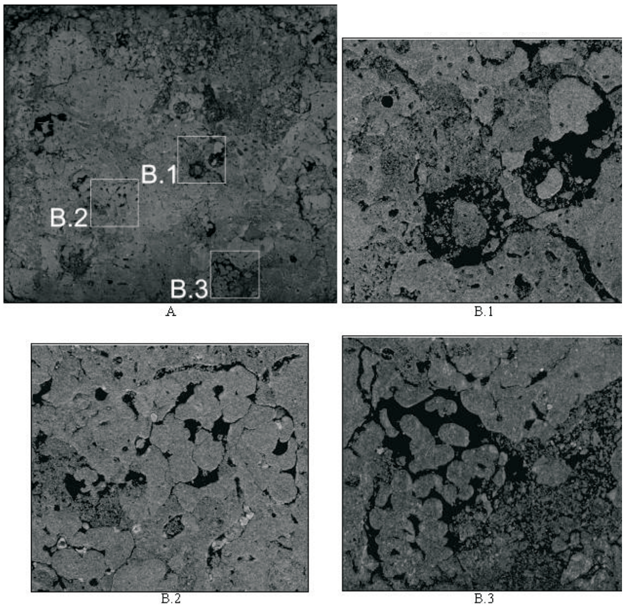

Fig. 10. Structure of the 40-48 cm layer of Ukrainian Haplic Chernozem. A – photograph in the 1:2 scale, B – sections 1-3 in the 2:5:1 scale. Explanations as in Fig. 6.

Soil in the 20-28 cm layer of the studied chernozem was much looser than in the upper layers (Fig. 8A). Numerous pores-channels intertwined and allowed for easy identification of aggregate edges. In the layer dominated porous and spongy structure. Regions of a complete aggregate structure were also visible in the enlarged sections (Fig. 8B). The soil structure in the three sub-layers of the 0-28 cm layer was comparable, however with the increasing depth the arrangement of solid soil constituents became looser. The analysis of opaque blocks revealed that the resulting status of soil structure was the effect of compaction of initial aggregate structure. It is worth mentioning, that the aggregates were characterized with a relatively high density – their interiors contained only a small number of tiny pores. The structure of soil in the 30-38 and 40-48 cm layers (Figs 9 and 10) was similar to the structure in analogous soil layers of the experiment I. At this depth numerous fissures became visible in the soil, and they were accompanied by channels made by moving soil fauna. The effect of soil fauna activity were also biogenic aggregates, frequently characterized with ideal spherical shape. As a consequence, the zones of aggregate structure developed in the areas of the greatest bioturbation. In the 40-48 cm layer abundant coprolites were moreover visible (Fig. 10B.2, B.3).

The evaluation of the structure of both chernozem pedons leads to a conclusion that the organic matter plays a significant role in maintaining favourable physical state of the studied soil under long-term agricultural use. Therefore agriculture should apply the proper cultivation technique and the crop rotation, which allow not only for preservation of the most amount of humus in soil, but also for its gradual increase in arable and sub-arable layer. One of the most effective methods of compensating for losses of soil organic matter, caused by its mineralization, is utilization of organic fertilizers.

CONCLUSIONS

1. The most visible differences between the soil structures of the two pedons occurred in their superficial layers. The 0-18 cm layer of the soil in experiment I was characterized with an aggregate structure, whereas analogous layer of the soil in experiment II was much more compacted and revealed some symptoms of consolidation.

2. Below about 30 cm from the ground level both pedons had very similar structure. In the deepest layer of the two pedons numerous effects of soil fauna activity – krotovinas, coprolites, and bioturbation were visible.

3. The appropriate crop rotation and regular supplies of organic matter allowed for preservation of a favourable aggregate structure of the soil in experiment I – even in the upper layers. On the other hand, the lack of organic fertilization of the soil in experiment II and the continuous cultivation of sugar beet caused visible compaction and disappearance of aggregates in the superficial soil layer.

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