ISSN 1064-2293, Eurasian Soil Science, 2013, Vol. 46, No. 6, pp. 660–667. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © V.A. Kholodov, 2013, published in Pochvovedenie, 2013, No. 6, pp. 698–706.

SOIL PHYSICS

The Capacity of Soil Particles for Spontaneous Formation of Macroaggregates after a Wetting–Drying Cycle

V. A. Kholodov

Dokuchaev Soil Science Institute, Russian Academy of Agricultural Sciences, per. Pyzhevskii 7, Moscow, 109017 Russia
E-mail: vkholod@mail.ru

Received February 29, 2012

Abstract—The capacity of soil particles for spontaneous formation of aggregates >0.25 mm was studied in a laboratory experiment. The particles from soil aggregates (3–1 mm) (initially aggregated particles, APs) and initially free particles (FPs) of <0.25 mm in size were isolated from the soddy-podzolic and chernozemic soils under fallow and from the arable soddy-podzolic soil. The aggregates of 3–1 mm were ground and passed through a 0.25-mm sieve. Then, the aggregates and free particles were poured with water and dried, and the content of the formed aggregates and their water stability were determined; in the samples from the arable soddy-podzolic soil, the organic carbon content was also determined in the newly formed aggregates. The FPs from the untilled soils formed almost no aggregates. At the same time, the APs from these soils manifested the ability for the spontaneous formation of aggregates, including water-stable aggregates. In the arable soddy-podzolic soil, on the contrary, both FPs and APs demonstrated the capacity for spontaneous self-organization into aggregates. The water stability of the self-organized aggregates from the arable soil was similar regardless of their source (APs or FPs). It was supposed that the ability of the FPs from the arable soil to form macroaggregates reflects the mechanical degradation of the aggregates in the soil: tillage results in the degradation of the aggregates, and the particles capable of spontaneously aggregation temporarily fall in the fraction of <0.25 mm. The water-stable aggregates produced from the APs or FPs of the arable soil contained more organic carbon (1.89%) in comparison with the water-stable aggregates separated from the initial 3- to 1-mm aggregates of this soil (1.31%).

Keywords: aggregates, self-aggregation, soil stability

DOI: 10.1134/S1064229313040078

INTRODUCTION

The soil structure includes the shape and size of the structural separates in the form of macroaggregates (peds) >0.25 mm in size, into which the soil is decomposed [15]. The structure of the upper humus horizons largely determines the essential properties of the soil, including its resistance to the impact of unfavorable environmental factors and its potential fertility [9, 15, 18]. Therefore, the study of the soil structure is of great importance for the regulation of the global carbon cycles [23], environmental protection, the reproduction of the soil fertility, and the optimization of the humus status in arable soils [6, 9, 15, 18, 19, 24]. Therefore, the study of the soil structure is of current importance.

In all the recent studies of the soil structure, the content of the structural separates is usually determined at the early stage or a specific size fraction is separated for the further investigation. The methods developed in the past century for the sieve separation of soil aggregates in air or water are mainly used [2, 12, 14, 15, 17, 21]. In the last years, the methods of separating soil aggregates were improved first by the standardization of the sieving time and frequency. The methodological recommendations were developed and mechanisms were designed for standardizing the procedure. Second, close attention was paid to the preparation of the soil aggregates for the water sieving [15].

In general, sieving methods are still widely used in soil studies. However, they have a significant limitation, which hampers the interpretation of the results: the principal nonselectivity of the method. In agronomic terms, along with the aggregates, the sieving isolates the pseudoaggregates: separates that have lower porosity than aggregates and high density; they are unstable in water or, on the contrary, absolutely stable because of cementation [11]. In addition, the average lifetime of soil aggregates in the environment is 27 days [22]; hence, the recently formed, mature, and near-degraded aggregates fall in the same fraction during the sieving. This suggests that their properties are different.

The aim of this work was to develop a method for the separation of soil aggregates composed of soil particles capable of spontaneously assembling into macroaggregates after a wetting–drying cycle, to substantiate its applicability for studying the structure of soil, and to use it for comparing the structures of a long-fallow soddy-podzolic soil and a chernozem, as well as an arable soil-podzolic soil.

For this purpose, the following problems should be solved:

(1) Studying the ability of self-organizing into structural separates of particles >0.25 mm in size from different sources: aggregated particles (APs) resulting from the mechanical degradation of the 3- to 1-mm fraction and structureless (free) particles (FPs) <0.25 mm in size occurring in the natural soil structure.

(2) From the obtained data, comparing the structural statuses of untilled soddy-podzolic soils and chernozems: to assess the difference in the content and distribution of the particles capable of self-assembling between the arable and the untilled soddy-podzolic soils.

(3) Studying the content of the organic carbon (C_{org}) in the self-assembled structural separates (including the water-stable ones) in the arable soddy-podzolic soil and comparing it to the content of C_{org} in the bulk soil, its structural separates, and the water-stable aggregates obtained by conventional methods.

In the proposed method, the major attention is paid to the air-dry soil aggregates 3–1 mm in size. The aggregates of 10–0.25 mm are usually considered as agronomically valuable components of the soil structure [11]. However, many authors think that the 3- to 1- or 4- to 2-mm fraction is the most favorable for crop growing. In 1933, Kachinskii indicated that "... aggregates of 1 mm already form an excellent fine-grained structure favorable for agriculture." The optimum size of the structural separates is most probably about 2–3 mm [4]. In 1947, the same author wrote "the permissible size range of the structural aggregates is from 1 to 10 mm, and the optimum size is 2–3 to 4 mm" [5]. Williams [3] considered structures of 2–3 mm in size as optimum and aggregates of 1 to 10 mm as agronomically valuable [3]. Khan [14] based his studies of the soil structure on the 3- to 1-mm fraction. In addition, the study of the C_{org} distribution in the structural separates of a chernozem showed that, in most cases, the carbon from the aggregates of 3–1 mm made the largest contribution to the soil organic matter [7]. Therefore, aggregates 3–1 mm in size were used for obtaining the APs.

The wetting–drying cycle was used to initiate the self-organization of the soil particles. On the one hand, this process is almost always cited as a structure-forming soil process [4, 5, 9, 11, 15], while, on the other hand, it is easily reproduced under laboratory conditions and little affects the properties of soils. In the course of the methodological study, an attempt was made to standardize the developed method to achieve good reproducibility in intra- and interlaboratory experiments.

Content of carbon and the pH values in the studied soils

Soil, land use	C_{org}, %	pH_{water}
Soddy-podzolic soil, Moscow oblast		
virgin	2.77	4.7
arable	1.31	6.3
Typical chernozem, annually mown steppe, Kursk oblast.	5.52	6.8

OBJECTS AND METHODS

The proposed method is based on the revealed ability of mechanically degraded APs to spontaneously form macroaggregates (aggregates >0.25 mm, hereafter referred to as aggregates) after a wetting–drying cycle under laboratory conditions.

Soils. The work was performed with soddy-podzolic soils sampled in Moscow oblast: a forest soil (under a spruce forest near the Chashnikovo Research and Training Experimental Station in Zelenograd district) and an arable soil of a grain–grass–row crop rotation (near the Dolgoprudnaya Experimental Agrochemical Station in Mytishchi district). Samples of a typical chernozem from the treatment of an annually mown steppe of a long-term experiment (the Alekhin Central Chernozemic Biosphere Reserve in Kursk oblast) were also studied.

A mixed soil sample was composed of five individual samples. Individual samples (about 2 kg each) were taken from the upper (A1) humus horizon at a depth of 5–15 cm on a plot about 5 m^2 in area. From the obtained sample (about 10 kg in weight), an average sample was made by quartering and separating the coarse roots.

In the samples, the content of organic carbon was determined according to the Tyurin method by digestion in potassium dichromate with spectrophotometric detection [8], and the pH was determined at a soil : water ratio of 1 : 2.5 [1]. The obtained values are given in the table.

In the studied soil series, the content of organic carbon varied from 1.31 to 5.52%, which corresponded to the range reported in the literature [12]. The regularly lower content of carbon in the arable soddy-podzolic soil compared to its native analogues should be noted.

The pH value varied from 4.7 in the fallow soddy-podzolic soil to 6.8 in the typical steppe chernozem (the values were typical for these soil types [12]). The pH value of 6.3 in the arable soddy-podzolic soil was due to the regular liming. In general, the considered parameters of the samples taken were typical for the studied soil types with consideration for the land use.

Method of preparing the structural soil separates capable of self-assembling, including the water-stable ones. For illustrative purpose, the developed fractionation scheme is given in Fig. 1. Two size fractions (3–

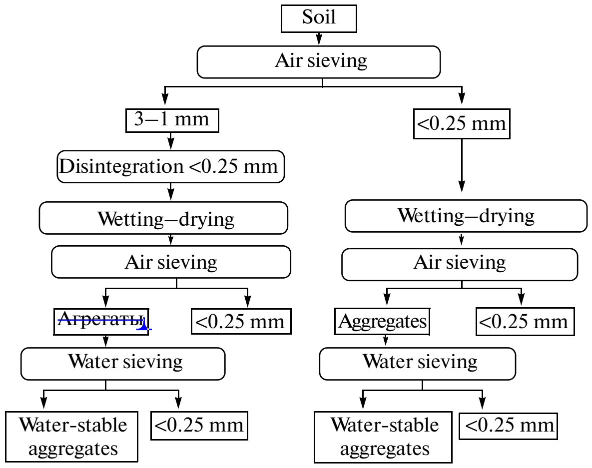

Fig. 1. Scheme of obtaining the soil structural separates used in the work.

1 and <0.25 mm) of air-dry natural aggregates were separated by sieving the air-dry soil material on a set of sieves (3, 1, and 0.25 mm mesh sizes).

The separated aggregates of 3–1 mm were triturated in a mortar and passed through a 0.25-mm sieve. The obtained APs (20 g) were placed in a Petri dish, and an equal amount of water (20 mL) was added. The mixture was air-dried at room temperature for two days. Analogous operations, except for the trituration, were performed for the FPs.

After drying, the particles formed a relatively homogeneous material composed of self-assembled aggregates and loosely bound particles. For their separation, the entire sample from the Petri dish was transferred into 50-mL plastic Falcon tubes with caps. For convenience, equal amounts of soil from one Petri dish were transferred into two tubes. The tubes were covered, placed in a rotator, and shaken at 25 rpm for 90 min.

The duration of the shaking was selected on the basis of the preliminary experiments, which showed that the content of the aggregates >0.25 mm decreased during the first 60 min, remained constant during the next 60 min, and then decreased again to values comparable with the experimental error (1–2%). The average contents of the aggregates separated after shaking for 60 to 120 min were close to the values obtained at the malaxation with a rubber pistil without pressure, but they had lower dispersion and better reproducibility.

After shaking, the soil from the tubes was weighed, transferred to a 0.25-mm sieve, and sieved to separate the self-assembled aggregates from the nonaggregated particles. The mass of the self-assembled aggregates was determined, and their portion in the sample was calculated.

To separate the water-stable aggregates composed of APs, the sample of self-assembled structural separates obtained at the previous stage was placed on a 0.25-mm sieve preliminary wetted by immersion in distilled water for 1 min. The soil was left to be wetted with the water retained by the sieve. If the content of the water on the sieve was insufficient, an overmoistened filter paper was applied to the sieve from the bottom (the paper was preliminarily immersed in water, and the excess water was left to flow down), and the aggregates were wetted to the level of the capillary water capacity.

The sieve with the aggregates was immersed in distilled water for 10 min. Then, the sieving was performed by swinging the sieve in water from the right to left by 45° and from the top down. The water-stable aggregates capable of self-assembling after mechanical degradation remained on the sieve. The obtained preparations of the water-stable aggregates were dried at 105°C.

The suspension with particles <0.25 mm passed through the sieve was dried in weighed porcelain cups and weighed. From the masses of the initial soil sample, the dry self-assembled aggregates, and their portion taken for the isolation of the water-stable aggregates, one calculated the content of the water-stable aggregates capable of self-assembling (the percentage of the self-assembled aggregates and the percentage of the initial soil sample).

The organic matter in the humus horizons is usually one of the main structure-forming agents [14, 18, 24, 25]; therefore, all the aggregates and particles obtained from the arable soddy-podzolic soil according to the described scheme were analyzed for their carbon according to the Tyurin method by digestion in potassium dichromate with spectrophotometric detection [8]. The obtained data were compared to the total C_{org} content in the water-stable aggregates isolated from the 3- to 1-mm soil aggregates by conventional methods [7, 15].

RESULTS AND DISCUSSION

Self-assembling of aggregates from preliminarily degraded structural separates of 3–1 mm and soil particles of natural consistence <0.25 mm after a wetting–drying cycle. The ability of mechanically degraded particles from structural separates of 3–1 mm and soil particles <0.25 mm to spontaneously assemble into aggregates (larger than 0.25 mm) was tested for both untilled soils (a typical chernozem of an annually mown steppe and a soddy-podzolic soil under a spruce forest) and an arable soil (a soddy-podzolic soil of a grain–grass–row crop rotation).

The contents of the particles that spontaneously assembled into aggregates for the considered structural separates of the untilled soils are given in the diagram visualizing the main statistical parameters for the obtained means (a box and whisker plot, $n = 4$) for each treatment (Fig. 2A).

No mechanical degradation of the aggregates occurs in the untilled soils; hence, all the particles capable of spontaneously assembling into structural separates >0.25 mm are already aggregated and almost do not exist in the free state.

The results obtained in the experiments with the components of the untilled soils confirmed the advanced supposition. Less than 2% of the aggregates were formed from FRs, which was comparable to the experimental error. This parameter made up 1.6% for the FPs of the typical chernozem and 0.2% for the soddy-podzolic soil. As can be seen (Fig. 2A) and was confirmed by the t test ($\alpha = 0.01$, $n = 8$), no significant differences were found between these two means. The obtained values were comparable to the experimental error; in addition, the visual examination of the obtained particles >0.25 mm showed that the plant roots <0.25 mm in diameter and longer than 0.25 mm made up no less than 50% of their mass. The particles of this shape do not always pass through the sieve, which largely explains the deviation of the analyzed parameter from zero. Thus, it can be concluded that the particles <0.25 mm in the untilled soils are almost not capable of self-assembling into aggregates.

According to the experimental data, the APs obtained by the mechanical degradation of the 3–1-mm aggregates from the untilled soils, on the contrary, have a pronounced ability for self-organizing. It can be seen that the 21.2% of APs from the typical chernozem and 6.1% of the APs from soddy-podzolic soil self-assembled into structural separates >0.25 mm in size. From the significance of the differences estimated by the t test ($\alpha = 0.01$, $n = 8$), both mean values differed from each other and from the mean contents of the aggregates self-assembled from the FPs.

Thus, the structural separates 3–1 mm in size contain particles able, after mechanical degradation, to spontaneously form aggregates after a wetting–drying cycle, and the particles of natural consistence <0.25 mm have no such ability. However, in the case of the soil tillage, which causes the mechanical degradation of the aggregates, the interrelations are more complex. For example, particles from decomposed aggregates can get into the <0.25-mm fraction. Therefore, the structural state of the arable soddy-podzolic soil used under a grain–grass–row crop rotation for a long time was studied.

In the arable soil, the FPs, as well as the APs, spontaneously formed aggregates after a wetting–drying cycle. Thus, 27.0% of the obtained APs self-organized again into structural separates >0.25 mm in size. When FPs were used, this parameter was equal to 15.3%. The obtained data are given in the diagram visualizing the main statistical parameters of the obtained mean values (Fig. 2B). It can be seen that the ranges of the main statistical parameters (the error and the standard deviation) of the obtained means do not overlap. This indicates that the content of the self-assembled aggregates depends on the source of the soil particles: at the use of mechanically degraded soil aggregates of 3–1 mm, this parameter is higher than for structureless soil particles. This conclusion is confirmed by the statistically significant difference between the analyzed means according to the t test ($\alpha = 0.01$, $n = 10$).

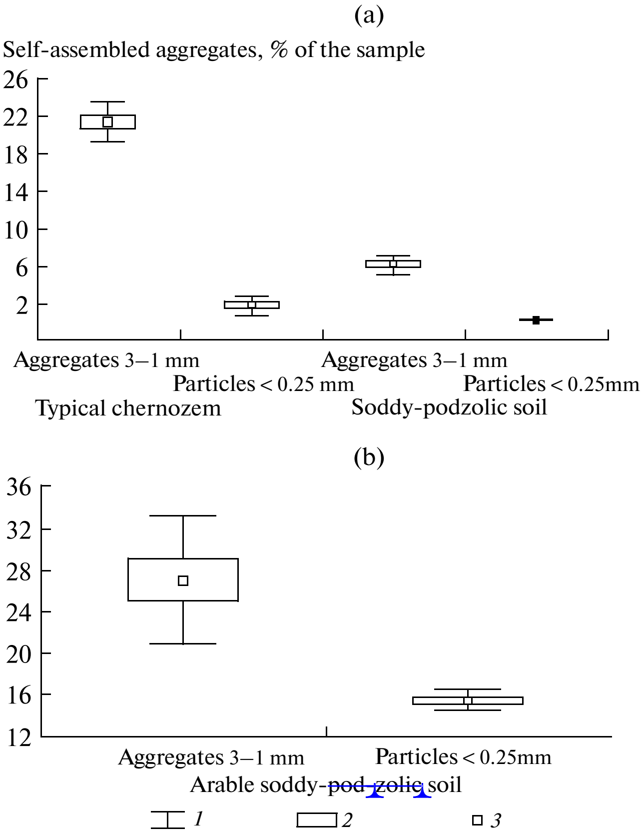

Fig. 2. Spontaneous formation of aggregates from structureless particles <0.25 mm of natural consistence (FPs) and particles obtained by the degradation of 3–1-mm aggregates to sizes <0.25 mm (APs) from (A) untilled soils and (B) arable soddy-podzolic soil. Here and below, the following designations are used: (*1*) standard deviation; (*2*) error of the mean; (*3*) mean.

Thus, the 3- to 1-mm aggregates of the soddy-podzolic soil contain almost 1.5 times more particles capable of self-assembling into aggregates compared to the FPs. The high capacity of the FPs from the arable soil to self-organize compared to those from the untilled soils is noteworthy. This can be related to the use of the soil of the grain–grass–row crop rotation. Some aggregates were degraded under the tillage, and their particles fell into the <0.25-mm fraction but retained their ability of self-assembling into aggregates at the moment of the soil sampling.

It should be noted that a significantly higher content of aggregates (27.0%) was spontaneously formed from the APs of the arable soddy-podzolic soil compared to the analogous untilled soil (6.1%). The observed relationships reflect the types of soil use. It is known that organic matter favors aggregation [14, 15, 18, 24]: the higher the content of organic matter, the higher the content of aggregates. There is a feedback

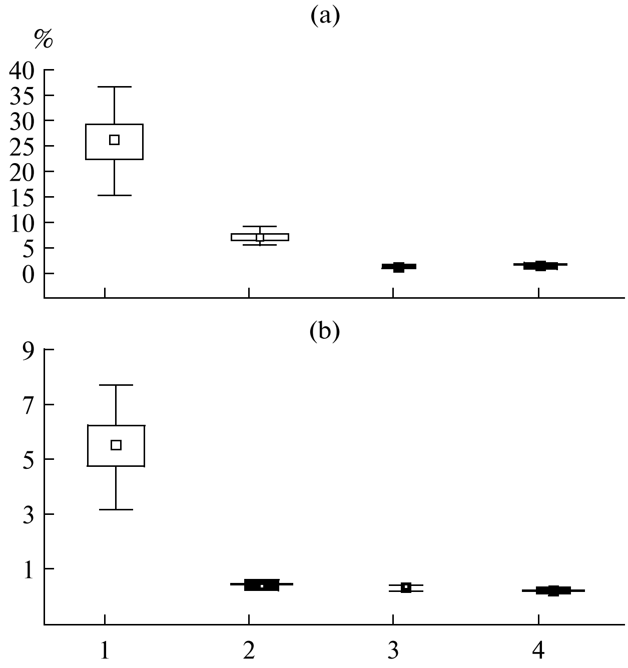

Fig. 3. Contents of water-stable aggregates in (A) the self-assembled structural separates and (B) the samples taken for obtaining these separates. The sources: (*1*) degraded 3- to 1-mm aggregates (APs) from a typical chernozem of an annually mown steppe; (*2*) degraded 3- to 1-mm aggregates (APs) from a soddy-podzolic soil under a forest; (*3*) degraded 3- to 1-mm aggregates (APs) from an arable soddy-podzolic soil; (*4*) structureless particles of natural consistence <0.25 mm (FPs) from an arable soddy-podzolic soil.

mechanism: the soil aggregates hamper the mineralization of the organic matter within them and thus retain it [18, 24]. In the arable soddy-podzolic soil, the aggregates are permanently degraded because of the tillage; self-assembling is one of the opposite processes. The self-assembling aggregates retain organic matter and, hence, are not degraded. At the same time, the particles not capable of aggregating after degradation lose carbon and, hence, the ability to form aggregates, even under an external impact. Therefore, the relative accumulation of particles able, after degradation, of spontaneously forming aggregates is observed in aggregates from the regularly tilled soil.

It should be noted that the presented data do not reveal the aggregation mechanisms in the soil, but they suggest a principal difference between the aggregate particles and the free particles <0.25 mm in the native and fallowed soils. It is possible that some APs have an affinity for each other and for FPs, which favors their aggregation after mechanical degradation. This behavior of APs can be due to their physicochemical features and probably their microbial population. This problem requires further investigation.

Along with the structural organization, the agronomically valuable soil aggregates should be water-stable. Therefore, the portion of water-stable aggregates in the obtained self-assembled aggregates was determined.

Water stability of the aggregates self-assembled from the preliminarily degraded structural separates. The dry self-assembled structural separates obtained at the previous stage were sieved in water through a 0.25-mm sieve. An extremely low content of aggregates was formed from the FPs of the untilled soils; therefore, it was insufficient for obtaining reliable results by water sieving. As was noted above, these separates contained more than 50% fine roots. Therefore, it can be stated with a high degree of probability that the water stability of these structural separates is of no diagnostic or practical value. Thereby, the aggregates isolated from the FPs of the untilled soils were not used in the further work.

The water stability was assessed for the aggregates self-assembled from the APs of all the considered soil types and the FPs of the arable soddy-podzolic soil. The water stability was estimated from the content of the water-stable aggregates.

The content of the water-stable aggregates in the self-assembled structural separates is given in Fig. 3A. The highest water stability (25.7% water-stable aggregates) was observed for the structural separates obtained from the APs of the typical chernozem under the annually mown steppe; the lowest water stability was found for those of the arable soddy-podzolic soil. The content of water-stable aggregates in the structural separates of the arable soil did not depend on the particles (APs or FPs) used for the self-assembling. The contents of the water-stable aggregates in these treatments were 1.2 and 1.4%, respectively; the mean values did differ significantly (the t test for $\alpha = 0.01$, where $n = 6$).

The absence of differences between the water stabilities of the self-assembled aggregates from the arable soil confirms the above supposition that a part of the aggregates was degraded because of the tillage of the soil in the grain–grass–row crop rotation and that their particles fell in the <0.25-mm fraction but retained their ability of self-assembling into aggregates at the moment of soil sampling.

The content of the water-stable aggregates in the structural separates self-assembled from the APs of the untilled soddy-podzolic soil (7.1%) was significantly higher compared to the arable soil (the t test for $\alpha = 0.01$, where $n = 6$) and lower than in the structural separates obtained from the chernozem FPs. However, in this case, the t test for $n = 6$ established significant differences only for the significance level of 0.05. This could be related to the small number of samples and the wide variation of the data on the content of the water-stable aggregates in the separates self-assembled from the APs of the typical chernozem (Fig. 3A).

At the qualitative level, the content of the water-stable aggregates in the obtained structural separates reflected the reported relationships between the water stability of the structure, the soil type, and the land use. The structure of the chernozem had high water stability compared to the soddy-podzolic soils; the virgin soddy-podzolic soil contained more water-stable aggregates compared to the arable soil [13, 14, 25]. However, the yield of the water-stable aggregates (Fig. 3B) calculated for the entire soil, i.e., for the soil sample taken to obtain self-organized structural separates, was significantly lower than the values reported in the literature [7, 13, 14]. For example, 38 to 88% of the water-stable aggregates were found in the 3- to 1-mm fraction in the study of the water-stable aggregates of the typical chernozem under different uses [7].

In our case, this parameter was equal to 5.5% of the initial sample of the 3- to 1-mm aggregates for the typical chernozem, 0.4% for the soddy-podzolic soil under a forest, 0.3% for the soil under the plowland, and 0.2% for the particles <0.25 mm of the arable soddy-podzolic soil. In the entire studied range of the means, only the value obtained for the 3- to 1-mm fraction of the chernozem was significantly different; the other treatments of the soddy-podzolic soils did not significantly differ from the *t* test ($\alpha = 0.01$, where $n = 6$). It can be seen that the content of the water-stable aggregates in the self-assembled separates of the chernozem is higher compared to the soddy-podzolic soils. The use of the soddy-podzolic soil had no effect on the parameter considered. However, further studies with a larger number of samples are required for obtaining a more substantiated conclusion.

To reveal the possible structural differences between the structural separates and the particles <0.25 mm obtained according to the developed scheme (Fig. 1), the content of carbon was determined in all the isolated samples of the arable soddy-podzolic soil.

Carbon content in the aggregates and particles <0.25 mm from the soddy-podzolic soil of the grain–grass–row crop rotation obtained during the experiment. For illustrative purpose, the content of carbon in the obtained structural separates is given together with the scheme of their separation in Fig. 4. The significance of the recorded differences was estimated by the *t* test for the significance level of $\alpha = 0.01$; the number of samples varied from 6 to 8.

The particles of natural consistence <0.25 mm in size obtained by dry sieving contained significantly more C_{org} compared to the entire soil and the air-dry aggregates of 3–1 mm. This is related to the inclusion of fine plant residues, which cannot be separated from the soil material at the preparation of the sample for the analysis, into the fraction <0.25 mm during the sieving. This is also the reason for the similar content of C_{org} in the particles that were not aggregated at the self-organization of the FPs (1.36%).

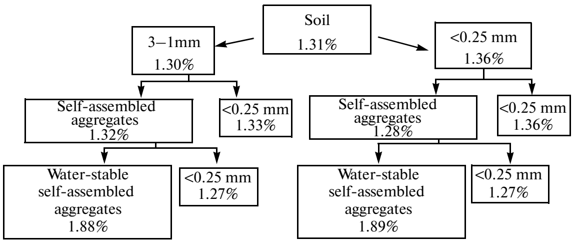

Fig. 4. Contents of organic carbon in the structural separates isolated from a soddy-podzolic soil of a grain–grass–row crop rotation according to the developed scheme (Fig. 1).

The mean contents of C_{org} for most other treatments were similar and belonged to the same population according to the *t* test ($n = 30$, $\alpha = 0.01$).

At the same time, a reliably higher content of C_{org} (1.89%) was observed in the water-stable aggregates obtained from the self-assembled structural separates. Its values were statistically equal for the water-stable aggregates obtained from the APs and FPs. Both values reliably differed from all the other mean values considered.

Thus, except for the effect of the undecomposed plant residues, it can be taken that most of the structural separates and particles <0.25 mm obtained according to the developed scheme contained similar amounts of C_{org}, which corresponded to its value for the entire soil (1.31%). However, the content of C_{org} in the water-stable aggregates of the self-assembled units was higher by about 40%.

The content of C_{org} obtained for the water-stable aggregates of the self-assembled structural separates was compared to its content in the water-stable aggregates obtained from the soil by conventional methods. For this purpose, the water-stable aggregates >0.25 mm were isolated from undisturbed soil aggregates 3–1 mm in size [7, 15], and their content of C_{org} was measured. The obtained mean value (1.56%) was reliably lower than the content of C_{org} in the water-stable aggregates of the self-assembled separates. It is notable that the content of carbon in the particles into which the water-unstable aggregates of 3–1 mm were disintegrated (1.17%) was reliably lower than that in the entire soil.

The higher content of C_{org} in the water-stable aggregates of the self-assembled structural separates compared to the water-stable aggregates obtained by the conventional method indicates their principal distinction; thus, the proposed method can be considered as a new method of acquiring information about the soil structure during which the fraction of the water-stable aggregates enriched with C_{org} is isolated.

When analyzing the concept of the soil aggregate hierarchy [18, 24, 26], one may attempt to elucidate the position of the isolated structural separates in the organization of the soil structure.

A principal approach to the concept of the soil aggregate hierarchy is the consideration of the soil aggregates as dynamic formations [24]. As was noted above, their lifetime in the soil is estimated at 27 days on the average [22]; therefore, it can be supposed that the recently formed, mature, and old (ready to be degraded) aggregates fall in the same fraction during the sieving in air and water. As was shown, the water-stable aggregates obtained using the proposed procedure contain significantly more C_{org} compared to the water-stable aggregates obtained by water sieving. Numerous data indicate a direct correlation between the content of the organic matter and the aggregate size and the water stability [7, 14, 24, 25].

All the aforesaid, as well as the proposed method of separation, which fractionates the particles capable of self-organization, suggests that this method isolates the freshly formed aggregates, which can impart to them the ability to self-organize.

The concept of the aggregate hierarchy involves the porosity exclusion principle [20, 24], according to which the efficiency of the binding agents depends on their sizes. The efficient agents have sizes comparable to pores, which should be passed through to link the particles. Organic and inorganic substances are able to bind particles into microaggregates; plant roots and fungal hyphae favor the binding of microaggregates into (macro)aggregates.

The obtained data on the capacity of the particles composing aggregates, after their physical reduction to the microaggregate size (<0.25 mm), of self-aggregating again suggest that some microaggregates can act themselves as binding agents for the formation of macroaggregates.

CONCLUSIONS

A simple, rapid, and informative method was proposed for studying the soil structure. The method is based on the ability of particles that compose soil aggregates, after their degradation, of self-organizing again into aggregates after a wetting–drying cycle.

The method allows the comparative estimation of the potential structure-forming capacity of a soil. If no mechanical degradation of the aggregates occurs in the soil, the particles of natural consistence <0.25 mm are not able to self-organize into aggregates after a wetting–drying cycle. On the contrary, such an ability of particles is an indicator of the mechanical degradation of the aggregates, e.g., tillage.

The higher content of particles capable of self-assembling in the aggregates of the arable soil compared to its untilled analogue indicates a feedback in the system: the degradation of aggregates–the loss of carbon. It is manifested in the relative accumulation of particles capable of forming aggregates after degradation and, hence, hampering the carbon loss.

The water-stable aggregates isolated from the self-assembled structural separates contain reliably more C_{org} compared to the water-stable aggregates isolated by the conventional methods.

It is possible that some soil aggregates can themselves act as binding agents for the formation of macroaggregates. They can be isolated by the developed method for obtaining structural separates capable of self-assembling after a wetting–drying cycle.

It can be supposed that the aggregates obtained by this method are recently formed and able to participate in the formation of the soil structure; they can be called active soil aggregates.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research, project no. 11-04-00284a.

REFERENCES

1. E. V. Arinushkina, *Handbook on the Chemical Analysis of Soils* (Izd. Mosk. Gos. Univ., Moscow, 1970) [in Russian].
2. A. F. Vadyunina and Z. A. Korchagina, *Methods for Studying Soil Physical Properties* (Agropromizdat, Moscow, 1986) [in Russian].
3. V. R. Williams, *Soil Science. Crop Science with Basics of Soil Science*, Collection of Works (Gos. izd. sel'skokhoz. lit., Moscow, 1951), Vol. 6 [in Russian].
4. N. A. Kachinskii, "On the Soil Structure," in *Proc. of the Russian Section of the International Soil Science Association. Commission 1. Soil Physics*, Vol. 1 (Moscow, 1933) [in Russian].
5. N. A. Kachinskii, "On the Soil Structure, Its Water Properties, and Differential Porosity," Pochvovedenie, No. 6, 336–348 (1947).
6. M. Körschens, "The Role of the Humus Content in Soil Fertility and Nitrogen Turnover," Pochvovedenie, No. 10, 122–131 (1992).
7. B. M. Kogut, S. A. Sysuev, and V. A. Kholodov, "Water Stability and Labile Humic Substances of Typical Chernozems under Different Land Uses," Eur. Soil Sci. **45** (5), 496–502 (2012).
8. D. S. Orlov and L. A. Grishina, *Practicum on Humus Chemistry* (Izd. Mosk. Gos. Univ., Moscow, 1981) [in Russian].
9. *Soil Science. Soils and Soil Formation.* Ed. by V. A. Kovda and B. G. Rozanov (Vysshaya shkola, Moscow, 1988) [in Russian].
10. *Soil Science. Types of Soils, Their Geography and Use*, Ed. by V. A. Kovda and B. G. Rozanov (Vysshaya shkola, Moscow, 1988) [in Russian].
11. B. G. Rozanov, *Soil Morphology* (Akademich. proekt, Moscow, 2004) [in Russian].
12. N. I. Savvinnov, *Soil Structure and Its Strength on Virgin, Fallow, and Long-Arable Plots* (Sel'kolkhozgiz, Moscow, 1931) [in Russian].

13. A. S. Frid, I. V. Kuznetsova, I. E. Koroleva, A. G. Bondarev, B. M. Kogut, V. F. Utkaeva, and N. A. Azovtseva, *Zonal–Provincial Norms of Changes in the Agrochemical, Physicochemical, and Physical Properties of the Major Arable Soils in European Russia under Anthropogenic Loads. Methodological Recommendations* Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2010) [in Russian].

1 14. D. V. Khan, *Organomineral Compounds and Soil Structure* (Nauka, Moscow, 1969) [in Russian].

15. E. V. Shein, *A Course of Soil Physics* (Izd. Mosk. Gos. Univ., Moscow, 2005) [in Russian].

2 16. E. V. Shein and E. Yu. Milanovskii, “The Role of Organic Matter in the Formation and Stability of Soil Aggregates,” Eur. Soil Sci. **36** (1), 51–58 (2003).

17. M. R. Ashman, P. D. Hallett, and P. C. Brookes, “Are the Links Between Soil Aggregate Size Class, Soil Organic Matter and Respiration Rate Artifacts of the Fractionation Procedure?,” Soil Biol. Biochem. **35** (3), 435–444 (2003).

18. E. T. Elliott, “Aggregate Structure and Carbon, Nitrogen, and Phosphorus in Native and Cultivated Soils,” Soil Sci. Soc. Am. J. **50**, 627–633 (1986).

19. F. Oliva, M. Oliva, and B. Sveshtarova, “Effect of Soil Macroaggregates Crushing on C Mineralization in a Tropical Deciduous Forest Ecosystem,” Plant Soil **259** (1–2), 297–305 (2004).

20. B. D. Kay, “Rates of Change of Soil Structure under Different Cropping Systems,” Adv. Soil Sci **12**, 1–52 (1990).

21. I. C. Mendes, A. K. Bandick, R. P. Dick, and P. J. Bottomley, “Microbial Biomass and Activities in Soil Aggregates Affected by Winter Cover Crops,” Soil Sci. Soc. Am. J. **63**, 873–881 (1999).

22. A. F. Plante, Y. Feng, and W. B. McGill, “A Modeling Approach to Quantifying Soil Macroaggregate Dynamics,” Can. J. Soil Sci. **82**, 181–190 (2002).

23. A. Rawson and B. Murphy, The Greenhouse Effect, Climate Change and Native vegetation. Background paper No. 7 (Native Vegetation Advisory Council NSW Dept. Land Water Conserv., 2000).

24. J. Six, H. Bossuyt, S. Degryze, and K. Denef, “A History of Research on the Link Between (Micro)aggregates, Soil Biota, and Soil Organic Matter Dynamics,” Soil Tillage Res. **79**, 7–31 (2004).

25. J. Six, K. Paustian, E. T. Elliott, and C. Combrink, “Soil Structure and Organic Matter: I. Distribution of Aggregate-Size Classes and Aggregate-Associated Carbon,” Soil Sci. Soc. Am. J. **64**, 681–689 (2000).

26. J. M. Tisdall and J. M. Oades, “Organic Matter and Water-Stable Aggregates in Soils,” J. Soil Sci. **62**, 141–163 (1982).

SPELL: 1. Organomineral, 2. Milanovskii