Aggregate Composition of Soils, Its Assessment and Monitoring

S. Yu. Bulygin* and F. N. Lisetskii**

Abstract—A set of parameters describing hierarchical levels of aggregate composition of soils is substantiated. High aggregation of arable soils is shown to depend on the soil biology and humus state. A two-level system that controls the aggregate composition is deduced, and principles for its operative monitoring are proposed.

A soil aggregate can be considered a product of many soil-forming processes. The totality of aggregates of different sizes and shapes constitutes the soil aggregate composition. The evaluation, control, and maintenance of the optimum aggregate composition should apparently become prerequisite for any agricultural activity.

Two hierarchical levels, macroaggregate and microaggregate, are usually distinguished in the aggregate composition. Discrimination between macroaggregates (>0.25 mm in diameter) and microaggregates (<0.25 mm) is substantiated physically by different aggregate stability: cohesion between elementary soil particles (ESPs) within microaggregates is an order of magnitude (more frequently, 2–3 orders of magnitude) stronger than that in macroaggregates (which are mainly built up of microaggregates). Evidently, macroaggregates and microaggregates also differ in organization. Although adhering to the concept of structural hierarchy (which implies that all levels are interdependent and form a system) [6], we should accept a certain independence of the levels. Therefore, it is a challenge to select a set of parameters that affords the most comprehensive and adequate description of each hierarchical level and predicts the trends of its evolution.

Voronin [6] claims that nonaggregated ESPs are present in all microaggregate fractions and that their ratio to microaggregates in a fraction depends on specific features of the soil-forming rock and the type of soil formation. Therefore, this ratio can, in general, be used as a characteristic of the microaggregate level. We have done an extensive search for the form of expression of this concept and verified it for various objects [1, 2]. The parameter of choice was the coefficient of aggregation after Beyer and Roades (proposed back in 1932) in our modification:

$$K_A = 100\frac{(a-b)}{a},$$

where a is the content of particles and microaggregates with diameters ranging from 0.05 to 0.25 mm, and b is the content of ESPs of the same sizes.

The content of nonaggregated ESPs and free microaggregates (not bound into macroaggregates) in fractions was determined by a direct counting in reflected light (MBS-9 microscope). Soil samples were preliminarily sieved for 30 s through a bank of sieves (0.25, 0.20, 0.16, 0.10, 0.065, 0.005 mm). After sieving, samples of macroaggregate fractions ($\Sigma > 0.25$ mm) were taken in appropriate proportions to yield a 25-g sample for wet sieving on a Baksheev instrument [3].

From the wet-sieve analysis, the weighted average diameter of water-stable aggregates was calculated. In the study, we used zonal soils of Ukrainian regions that show rather diverse edaphic and climatic conditions: the left bank forest–steppe, Donetsk steppe, and dry steppe of the Bug basin. Soil evolution was highlighted by using archeological datings of buried soils from croplands of the ancient state of Olbia.

In soil assessment, the aggregate stability is the most important characteristic at the macroaggregate level. A true aggregate should first of all be stable in water, which depends directly on the content of humic substances [4]. The weighted-average diameter of water-stable aggregates is considered the most integral and informative index of their stability [7]; therefore, we select it as the base parameter in describing the macroaggregate level.

With allowance made for the above, we propose a two-level system for monitoring the aggregate composition of the soil. Each monitoring level (which corresponds to some hierarchical level of the aggregate composition) has its own monitoring parameter or set of parameters. In our opinion, the following parameters of the macro- and microaggregate levels are rather informative and easy to determine: $\bar{d}$ (mm), the weighted-average diameter of water-stable aggregates, and K_A, the coefficient of aggregation (Fig. 1).

Soils exposed to different management systems and differing significantly in their humus state show a relative independence of macro- and microaggregate levels. For arable soils, the efficiency of participation of humus in microaggregation does not correlate with the

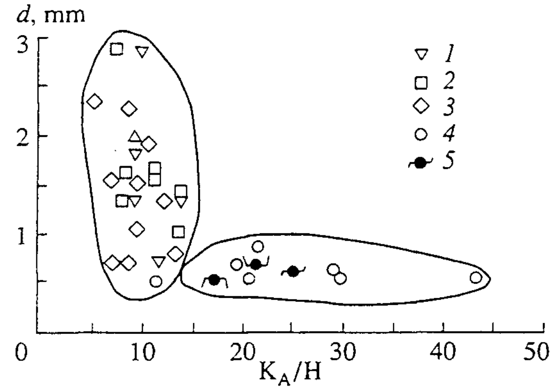

Fig. 1. Weighted-average diameter of water-stable aggregates ($\bar{d}$) vs. the aggregating efficiency of humus (K_A/H) in 20-cm topsoil of southern chernozems and dark chestnut soils of the Bug Basin: (*1*) virgin fully developed soils, (*2*) young soils of different age, (*3*) long-fallow soils, (*4*) old arable soils (ancient and present-day), and (*5*) arable soils (cultivated for the last 130–150 years).

diameter of water-stable aggregates. For soils formed under natural vegetation, the higher water stability is not related to higher microaggregation and is independent of the efficiency of humus. Obviously, physicochemical parameters alone are insufficient to compare soils exposed to such different conditions.

The soil biology also differs radically. The importance of root assemblage of zonal plant associations for soil fragmentation and structure formation is proved by the ratio of the live root weight to the soil weight (for the steppe zone, see Table 1). The 20-cm soil layer under natural vegetation is saturated with roots 3–4 times greater than the arable horizon. Compared to arable soils, virgin and long-fallow soils have much greater total porosity (including the passage ways of earthworms and the pores formed in places of decomposed roots) and intra-aggregate porosity [6]. Under natural soil formation, all this favors growth of fungal hyphae, whose contribution to the aggregate stability has been proved experimentally [12] and is supported by the well-known dynamics of the water stability [4]. Earthworms are capable of forming a coprolite layer as thick as 5 mm per year, thus strengthening topsoil aggregation [5].

A broad series of zonal arable soils (from soddy podzolic to dark chestnut) shows an intimate dependence ($r = 0.89 \pm 0.19$) of K_A on the humus content in the 20-cm topsoil. Within the zone (southern chernozems and dark chestnut soils in the southern part of the Bug Basin), K_A and the humus content are not correlated (Fig. 2). This probably results from the drastically smaller range of the humus content variation (1–2.8%). The latter soils have high degree of microaggregation (K_A = 31–48%), and this suggests a more complex mechanism of aggregation, involving different humus substances.

Note that the water stability of aggregates has been left out of the discussion for the time being. After Khan [11], an agronomically favorable soil aggregation is produced by organomineral compounds, provided that the following three components are obligatorily present: newly formed humus, highly dispersed clay minerals, and exchangeable bases. In heavily cultivated arable soils with small input of plant debris, the contribution of newly formed humus to aggregation is negligible, and the observed humus content (1.1–2.8%) can be attributed to strong organomineral colloids ("which conserve humus for centuries and millenia," according to Aleksandrova). Hence, microaggregation of arable and old arable soils can primarily be related to effects of polymeric colloids whose aggregation efficiency is similar to that of humic substances [8]. The search for specific features of the group and fractional composition of humus in arable soils is also interesting.

In soils formed under natural vegetation (virgin or long-fallow soils, in which humus is reproduced

Table 1. Underground phytomass in virgin plant associations and warm-zone agrophytocenoses (southern chernozem)

Agrophytocenosis	Soil layer, cm	Roots K_1	Live roots K_2	Dead roots	$\frac{K_1 + K_2}{W}$
		g/m^2			
Forb–fescue association	0–10	48.5	834.5	283.0	7.3
	0–20	65.0	1074.5	413.0	4.8
Feather grass–fescue association	0–10	72.5	717.5	1159.5	6.6
	0–20	87.0	870.5	1465.5	4.0
Alfalfa (4 years)	0–10	275.8	202.8	61.6	4.0
	0–20	392.0	376.0	97.6	3.2
Winter wheat	0–10	No	204.0	No	2.0
	0–20	"	270.7	"	1.4
Maize	0–10	"	160.4	"	1.6
	0–20	"	243.3	"	1.2

Note: *W* is the soil weight in the corresponding layer, kg/m^2.

steadily), the humus content correlates with microaggregation (Fig. 2). Comparing the regression coefficients of the correlations between K_A and the humus content in the zonal and intrazonal soils, we logically conclude that humus of arable soils containing considerable amounts of nonspecific humic substances has a different quality. This makes it necessary to account for the aggregating efficiency of humus. To do this, we propose to use the parameter K_A/H, the degree of aggregation per 1% of humus of the given soil.

Arable soils have lower humus content than fully developed virgin, young, and long-fallow soils. However, the aggregating efficiency of humus does not correlate with the degree of dehumification (Table 2). The increased microaggregation of arable soils is therefore a point of primary importance. Inspection of the group and fractional humus composition shows that microaggregation correlates with the content of humic acids that are free or bound with mobile sesquioxides. Their content in arable soils is 2–3 times higher than in virgin soils. We believe that, together with water-soluble humus, this fraction can play an important role in saturation of humic substances with functional groups that generate peripheral elements for the formation of heteropolar organomineral compounds (which, in turn, form mobile associates and microaggregates [9, 10]).

Of most interest is the well-defined dependence of the aggregating efficiency of humus on the content of reactive fulvic acids (free or bound with mobile sesquioxides). This, however, only brings us close to the point. The entire mechanism of the humus effect on microaggregation remains to be elucidated. Although nonspecific organic compounds can be an important component of the acid-soluble organic matter of virgin and long-fallow soils, all the soils we studied were distinguished by the highest content of reactive fulvic acids (15–26%). Apparently, this specific feature is closely related to the primary role that the fulvic acid fraction of labile humus plays in the formation of agronomically optimal structures in arable chernozems [10]. This was supported by a stationary experiment. For example, by using annual surface tillage, instead of moldboard plowing, for all crops of the crop rotation over ordinary chernozem, a substantial increase in the content of fulvic acids was observed in parallel with an increase in the total humus content after only five years. This implies the possibility for ESP aggregation to be monitored. Therefore, in arable soils, labile fractions of humus substances are not only reproduced more intensely (compared to virgin soils) but have a higher aggregating capacity as well. This explains the decrease in the total of unreacted ESPs as a function of the cultivation time (from 18–34% on virgin soil to 6–20% on croplands cultivated for different periods), a seemingly paradoxical dependence.

Archaeological and historical datings allow us to plot $\bar{d}$ versus cultivation time (Fig. 3). The weighted-average diameter of water-stable aggregates decreases by a factor of 2–3 after only 100–150 years; after 1000 years, it reaches a steady-state value of 0.50–0.75 mm. This fact suggests that arable soils show a stable zonal index of erosion stability, which depends on genetic characteristics of the soil (e.g., the coefficient of aggregation) and not on the agrophysical state of the topsoil. Naturally, a different intensity or duration of soil cultivation will result in a different range of variation.

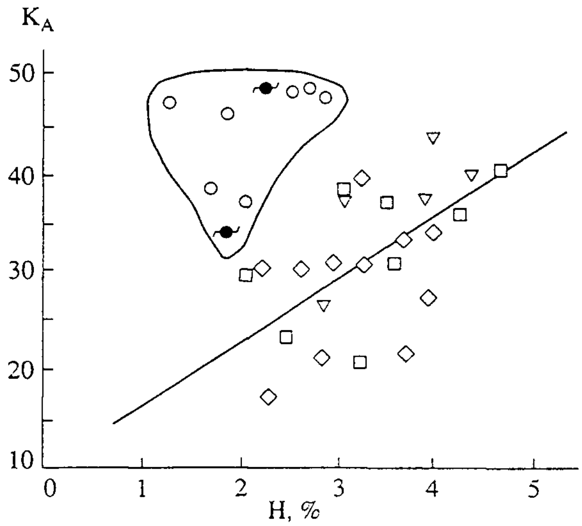

Fig. 2. Coefficient of aggregation K_A vs. humus content H in the 20-cm topsoil of arable and newly cultivated soils: $K_A = 6.2H - 10.43$; $r = 0.63 \pm 0.34$. For designations, see Fig. 1.

The range of $\bar{d}$ variation under a certain management system depends on many factors, including tillage technology. Our studies show that occasional application of any primary tillage yields statistically significant different $\bar{d}$ values as soon as autumn. The differences become stronger by spring, but by the time of harvesting, the effect of primary tillage vanishes. The limits of the range of $\bar{d}$ are much more difficult to change. The challenge is to raise the lower limit, which can serve as a quantitative parameter of the management system: the management system should be profitable and ecologically nonhazardous and should retain the soil fertility in case of climatic hazards with at least 10% probability. Therefore, the value of the lower decile $\bar{d}_{0.1}$ can reliably characterize the lower limit of the steady-state variation range.

A stationary field experiment on ordinary chernozem (Donetsk Steppe) assayed different soil tillages for crops of a ten-course crop rotation: moldboard plowing, subsoil (chisel) tillage, blade tillage, and surface tillage. By the fifth spring, $\bar{d}_{0.1}$ of the 20-cm topsoil was 0.34, 0.43, 0.36, and 0.45 mm in variants, respectively; 2.00 mm on the mowed virgin soil; 0.40, 0.40, 0.50, and 0.63 mm in summer, when the erosion hazard from rainstorms is at a maximum; and the virgin

Table 2. Aggregating efficiency of humus in soil under different management systems

Soil	Number of determinations	K_A	H, %	K_A/H
	$x_{min} - x_{max}/x_{av}$			
Virgin	6	22–43/31	2.78–4.21/3.47	8–11/9.5
Young	9	21–39/31	2.16–5.35/3.55	5–13/9
Long-fallow	10	18–38/29	2.28–3.87/3.16	7–13/9.5
Arable	17	34–48/42	1.51–2.76/1.95	17–25/22
Old arable	7	27–48/42	1.11–2.19/1.89	11–43/24

soil showed no change in $\bar{d}_{0.1}$. Hence, the improvement of the humus state raised the lower limit of the range of the water stability of macroaggregates. This proves that agricultural activity allows one not only to monitor the seasonal variation of the macroaggregate water stability but also to change deliberately the limits of this variation, that is, to improve the steady, inherent water stability of soil aggregates. The development of rational soil-protecting plant cultivation requires a sound scientific basis. Prerequisite is a quantitative description of the effects of all individual technological operations on the soil aggregate state; in other words, operative monitoring of the aggregate composition in cultivation is needed.

The monitoring could obviously be done with respect to K_A and $\bar{d}$. The sensitivity of these parameters is too low to be used in assessment of separate operations. For monitoring of the aggregate composition to be more effective, some additional parameter is needed. The content of nonaggregated ESPs changes shortly after cultivation, within a certain range after any tillage [1, 2]. Maintaining the content of nonaggregated ESPs around the upper or lower limit, we thereby dictate a change in aggregate composition. For soils of the Donetsk Steppe ($\bar{d}$ = 0.50–0.75 mm), the total amount of nonaggregated ESPs was shown to vary between 5–15%; we therefore can speak about an inverse proportional relationship between $\bar{d}$ and the content of nonaggregated ESPs, hereinafter designated by C.

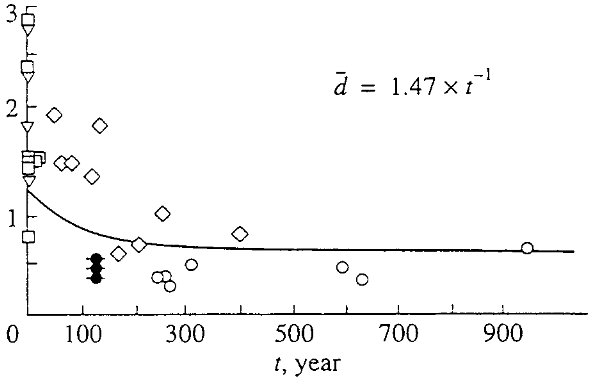

Fig. 3. Weighted-average diameter of water-stable aggregates $\bar{d}$ vs. cultivation time. For designations, see Fig. 1.

The stationary field experiment showed well-defined cyclic variations of C during the agricultural year. The amplitude and phases of this cyclic variation were affected primarily by the technology of soil cultivation. Nearly any cultivation operation increases the value of C (which then starts to decrease). It is likely that the lower decile $C_{0.1}$ will be the most complete and adequate characteristic of the effect of soil cultivation on the content of nonaggregated ESPs, as was the case with the $\bar{d}$ series. This parameter describes the extent of restoration of aggregation after cultivation. Lower values of C are more favorable, since this parameter characterizes the degree of aggregate breakdown to ESPs. The above statement is well illustrated by the $C_{0.1}$ values for the 20-cm topsoil in variants: 8.4, 6.2, 4.1, and 4.0%. Moldboard plowing produces the greatest effect on aggregates, which have no time to recover the initial state; the water stability of the aggregates decreases. The use of tillages that maintain $C_{0.1}$ at close to 4% afforded an increase in water stability of macroaggregates compared to moldboard plowing. This apparently resulted from an increase in the total amount of humic substances in the soil. Therefore, maintenance of nonaggregated ESPs at an excessively high level (which occurs with moldboard plowing) increases the rate of humus mineralization and, therefore, deteriorates the aggregate composition. Note that this is merely a hypothetical statement that needs experimental substantiation.

To establish a scientific basis for monitoring the aggregate composition with respect to the content of nonaggregated ESPs (which would evaluate the efficiency of separate operations and the management system as a whole), the limits for the content of nonaggregated ESPs should be specified. We believe that this goal can be achieved in a reliable and simple manner: the content of nonaggregated ESPs under perennial grass (3–4 years old) can serve as a standard for soil varieties of similar genesis. By this time, the soil loses features imparted by tillage before grass sowing, and the minimum ESP content characteristic of heavily cultivated soils is acquired.

Hence, we propose that monitoring of the soil aggregate composition be done with respect to a parameter reflecting the state of the preceding hierarchical level (having a lower degree of organization)—the state of nonaggregated ESPs. This principle reflects the results of degradation processes occurring primarily in a subordinate organization level. This approach is apparently more universal and can be considered the underlying concept in soil monitoring.

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