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APPLIED PROBLEMS OF ARID LAND DEVELOPMENT

Aggregation Formation in Chestnut and Meadow–Chestnut Soils of the Terek–Sulak Plain and Its Impact on Their Agrophysical Properties

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Abstract—The physical properties of plowed and fallow chestnut and meadow–chestnut soils were studied in the Terek–Sulak Plain. It is shown that soil density depends both on the aggregate size and specific features of the soil formation process. In each particular case, this dependence is closely linked to the soil genesis and agricultural use. Analysis of the aggregate porosity estimated based on the percentage content of fractions shows that the major share of interaggregate porosity is attributed to large aggregates. The results can be extrapolated to other parts of the soil cover in the study area. On each studied site, an experimental soil profile cut was established, the morphological soil properties were described, and soil samples were taken layer by layer (cm) from horizons A, B_1, B_2, and C_1 (A_{plow}, arable layer) for chestnut soils and from horizons A, B_1, and C_1 for meadow–chestnut soils. The structure index was computed based on the the sifting data as the ratio between the sum of macroaggregates (0.25–10 mm in size) and the sum of aggregates with diameters of more than 10 mm and less than 0.25 mm. The porosity of aggregate fractions 7–5, 5–3, 3–2, 2–1, 1–0.5, and 0.5–0.25 mm in size was determined from randomly selected samples of the respective fractions. Mechanical sampling was used to ensure the random selection of samples for analysis. In all of studied soils, the porosity of aggregates of the same size decreases down the profile. The sharpest decrease is observed in large (7–5 mm) aggregates: their porosity drops from 37% in horizon A to 31% in horizon C_1. In small aggregates, this trend is manifested not so clearly. In chestnut soils, aggregate porosity gradually decreases with depth, while the minimum porosity in meadow–chestnut soils is observed in the B_1 and C_1 horizons. This pattern is manifested most clearly in aggregates 2–1 mm in size. However, the minimum aggregate porosity in horizon B_1 is pronounced quite clearly not only in the 2–1 mm fraction but also in all other fractions up to 7–5 mm in size. In the C_1 horizon, the aggregate porosity drops to almost identical values that are close to the computed close-packed porosity (a method involving mutual coupling of mineral particles in a clastic rock). Earlier studies have shown that aggregate porosity is closely linked to the soil composition, structure, and origin, as well as the general soil genesis that determines the fertility.

Keywords: soil structure, aggregate, density, porosity, genetic horizon

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INTRODUCTION

The structural–aggregate state of soils is a key factor in the optimization of their physical properties (Morkovkin and Demina, 2011). Transformations affecting the agrogenic component of the soil resources in agricultural lands as a result of long-term agroevolution processes and subsequent activation of degradation processes lead to deterioration of the agrophysical soil properties in the arable horizon and disintegration of the soil structure (Lebedeva et al., 2013). These changes are interrelated with such processes as depletion of the structural–aggregate state of soils, changes and a decrease in the percentage ratio of humus composition and fractional–group composition, a decrease in the share of underground biomass, the consequent reduction of the phytocoenosis productivity, the low intensity of carbon dioxide emissions from the soil, and a decrease in the humus content.

The distribution of aggregate components by size has a positive effect on the soil agrophysical properties and, hence, on the yield of agricultural plants; however, the structure, composition, porosity, and size of the aggregates are also important. Kachinskii (1963) showed in his works that only porous aggregates have a core agronomic value. Studies of gas diffusion in soils show that aeration of plant roots and soil microorganisms depends not only on the interaggregate porosity but on the aggregate porosity as well. The soil structure porosity primarily reflects the influence of the soil formation process and the long-term agricultural use of soil (Currie, 1961, 1965).

Based on the coagulation theory of structure formation, Kachinskii (1965) theorized that the porosity of aggregates should go down as their size decreases. Concurrently, Vershinin (1958) established that the porosity of lumps obtained from the crushing of compact water-resistant mass produced from ground soil via its impregnation with peat glue into aggregates of different sizes does not depend on the aggregate size and is close to 39%.

The American scientists Wittmuss and Mazurak (1958) studied the physical and chemical properties of aggregates isolated from the surface horizon of a brunizem soil and established that the aggregate density increases as their size decreases.

However, other American researchers, Tabatabai and Hanway (1968), established that the bulk density of aggregates in some soils of Iowa (United States) slightly decreases as their size decreases; in another soil series, this parameter virtually does not change. These trends are manifested especially clearly in aggregates from the subsurface horizons of the studied soils. A negative correlation between the bulk density and the soil carbon content was noted for each fraction of aggregates.

Apparently, the inconsistencies in the data obtained for different soils indicate the absence of a universal relationship between the porosity of aggregates and their size. In each particular case, this relationship is closely linked to the soil genesis and agricultural use.

Density is one of the most important physical soil properties; the value of this dynamic parameter is determined via the summation of the densities of the arable and subsurface layers. The loosest soil condition is observed immediately after cultivation. Over time, it is gradually compacted; after a while, the soil density returns to the equilibrium state (i.e., it changes insignificantly until the next treatment). The upper soil horizons, which contain more organic matter, are better structured, and are loosened during cultivation, have a lower density. In the natural environment, soils affected by compaction and loosening processes ultimately reach an equilibrium density; this state reflects an equilibrium between the soil porosity and its solid phase. Each soil type is distinguished by its own density. Structured soils feature smaller intervals between the optimal and equilibrium density values, while these values in cultivated soils may coincide (Slesarev, 1984; Shevlyagin, 1963). The equilibrium (real) and optimal soil densities do not always coincide. The optimum density range is 1.1–1.25 g/cm^3. The optimum density for grain crop cultivation lies in the range of 1.1–1.3 g/cm^3. For example, an increase in the density of a heavy loamy soil to 1.4–1.5 g/cm^3 can reduce the total harvest by half. Density values over 1.4–1.45 g/cm^3 in the subsurface layer also have an adverse effect on the yield (Kushnarev and Pogorelyi, 2008).

Analysis shows that soils of the Terek–Sulak Plain are diverse in composition and belong to the following types: meadow–chestnut soils (61%), chestnut soils (some 13%), and solonchak soils, which are widespread throughout the soil cover (11%).

The purpose of this study was to perform a comparative analysis of changes in the aggregate composition of various soil types (chestnut and meadow–chestnut soils) that occur in the course of their postagrogenic development and determine the efficiency of soil resource utilization in agricultural lands of the Terek–Sulak Plain, Republic of Dagestan.

EXPERIMENTAL

The subjects of this study were arable and fallow lands of the Terek–Sulak Plain of the Republic of Dagestan that are actively used in agriculture. Descriptions were produced for the chestnut and meadow–chestnut soils in these agrolandscapes that are affected by various land uses.

The studied sites feature a stable, temperate, continental climate: the summers are hot, and the winters are relatively mild.

In early 2017, experimental works were launched and soil profile cuts established in the central part of the Terek–Sulak Plain to determine the agrophysical properties of local soils (Terpelets and Slyusarev, 2016). The studied sites were selected based on their location: all of them are confined to leveled watersheds that are typical for the studied soil subzones and feature characteristic bioclimatic conditions and plant communities. On each studied site, an experimental soil profile cut was established, morphological soil properties were described, and soil samples were taken layer by layer (cm) from horizons A, B_1, B_2, and C_1 (A_{plow}, arable layer) for chestnut soils and from horizons A, B_1, and C_1 for meadow–chestnut soils.

The soil density was determined with a cylinder–borer of a known volume (100 cm^3). To assess the structural and aggregate composition, air-dry soil samples weighing 1–1.5 kg were fractionated on a standard set of sieves (dry sieving according to the Savvinov's method). The structure index was computed based on the sifting of data as the ratio between the sum of macroaggregates (0.25–10 mm in size) and the sum of aggregates with diameters of more than 10 mm and less than 0.25 mm (Vadyunina, 1986).

Figure 1 shows the results of the aggregate analysis. The porosity of aggregate fractions 7–5, 5–3, 3–2, 2–1, 1–0.5, and 0.5–0.25 mm in size was determined from randomly selected samples of the respective fractions. Mechanical sampling was used to ensure the random selection of samples for analysis.

The statistical processing of the experimental data involved variance analysis (Dospekhov, 1985).

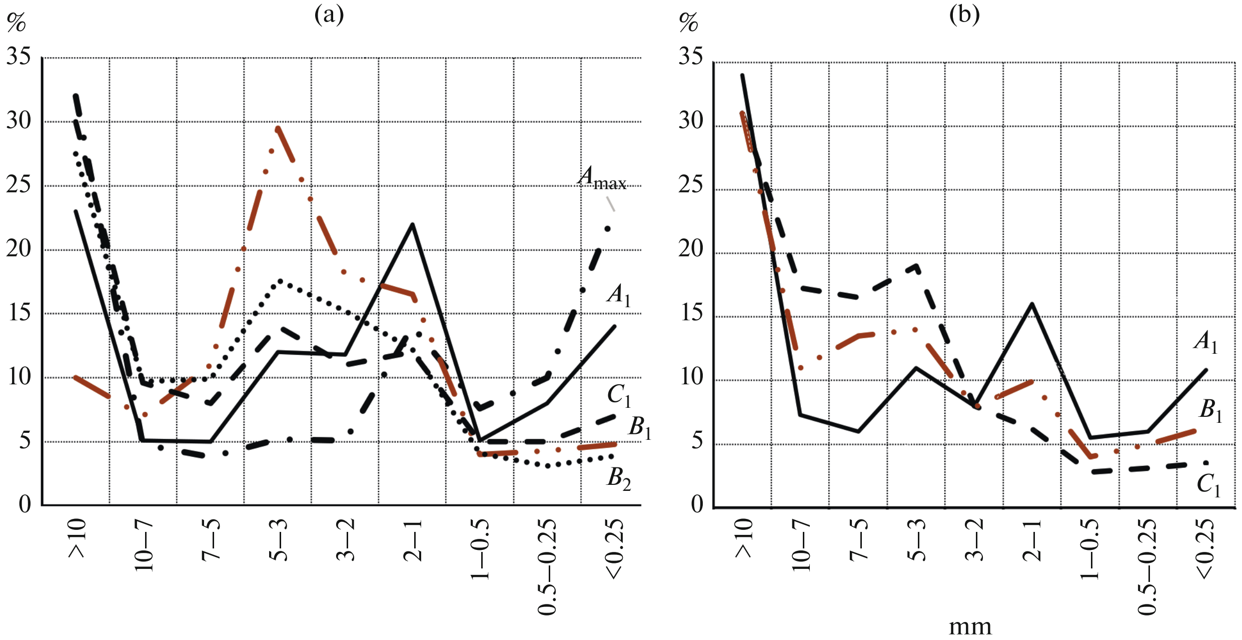

Fig. 1. Aggregate composition (%) of the studied soils by the fraction size (mm): (a) chestnut soil; and (b) meadow–chestnut soil.

According to Zakharov (1954), soils can be classified by the aggregate shape into the following types: blocky lumpy structure, granular structure, nutty structure, prismatic structure, columnar structure, platy structure, lamellar structure, leafy structure, and scaly structure.

The studied chestnut soils feature a silty–lumpy structure in the A_1 horizon and a prismatic–nutty structure in the B_1 and B_2 horizons. The C horizon features a blocky structure in all studied soils. Data on the mechanical, mineralogical, and chemical composition, as well as physical properties of the studied soils, are available in our earlier publications (Teimurov, 2019; Teimurov et al., 2020).

RESULTS AND DISCUSSION

Some lands of the Terek–Sulak Plain have been withdrawn from agricultural use due to their degradation in the course of the transition to the market economy and currently remain in the fallow state. This situation has generally mitigated some of the agroenvironmental problems. The overall degradation of chestnut soils and the consequent decrease in yield, however, have necessitated a detailed examination.

The data provided in Table 1 indicate that the density of aggregates, regardless of their size, is significantly higher than the density of the undisturbed soil; this applies to all studied soils. As the size of aggregates decreases, their density generally increases. This trend is manifested more clearly in the subsurface horizons. The density of aggregates also increases with depth; this applies to all aggregate sizes.

As can be seen from Tables 2 and 3, the total porosity in all genetic horizons of the studied soils is higher than the porosity of individual aggregates regardless of their size. The total porosity decreases down the profile due to the reduction of the interaggregate and aggregate porosity. However, in different genetic horizons, the decrease in the total porosity may be determined by different mechanisms.

As the aggregate size decreases to 2–1 mm, a statistically significant (at a confidence level of $P = 0.999$) decrease in the aggregate porosity is noted in the humus-accumulative horizons of all studied soils. Currie (1966) believes that aggregates of this size most accurately characterize the aggregate porosity. Larger aggregates may contain pores comparable to interaggregate ones in size, while aggregate fractions <1 mm may contain gravelly and sandy elementary soil particles that also distort the aggregate porosity. In most cases, changes in the porosity of aggregates <1 mm are statistically insignificant.

In all studied soils, the porosity of aggregates of the same size decreases down the profile. The sharpest decrease is observed in large (7–5 mm) aggregates: their porosity drops from 37% in horizon A to 31% in horizon C_1. In small aggregates, this trend is manifested not so clearly. It must be noted that the aggregate porosity in chestnut soils gradually decreases with depth, while the minimum porosity in meadow–chestnut soils is observed in the B_1 and C_1 horizons. This pattern is manifested most clearly in aggregates 2–1 mm in size. However, the minimum aggregate porosity in horizon B_1 is pronounced quite clearly not only in the 2–1 mm fraction but also in all other frac-

Table 1. Aggregate density in various horizons of the studied soils

Horizon index and depth, cm	Specific density of the eolian phase	Soil bulk density, g/cm^3	Aggregate bulk density, g/cm^3 in dependence to the fraction size, mm					
			7–5	5–3	3–2	2–1	1–0.5	0.5–0.25
Soil and land use type								
Chestnut, calcareous, middle loamy soil; long-term fallow land (desert steppe, Kizilyurt district)								
A 5–15	2.59	1.31	1.61	1.69	1.76	1.75	1.76	1.75
B_1 21–34	2.68	1.32	1.83	1.87	1.90	1.92	1.91	1.87
B_2 35–45	2.73	1.40	1.86	1.88	1.92	1.92	1.92	1.88
C_1 46–65	2.74	1.50	1.89	1.88	1.90	1.89	1.88	1.89
Chestnut, calcareous, light loamy soil; arable land (wheat, Kizilyurt district)								
A_{plow} 0–20	2.69	1.17	1.65	1.69	1.76	1.84	1.86	1.88
Meadow–chestnut slightly solonetzic heavy loamy soil; long-term fallow land (a former alfalfa field, Khasavyurt district)								
A 6–28	2.63	1.20	1.76	1.73	1.81	1.83	1.85	1.89
B_1 29–60	2.71	1.39	1.88	1.89	1.91	1.93	1.93	1.94
C_1 72–150	2.72	1.55	1.95	1.95	1.96	1.98	1.98	1.94

For each unbroken soil sample, the bulk weight was determined with a fivefold replication; the same numbers of replications were used to determine the bulk weight and porosity of aggregates.

Table 2. Aggregate porosity in various horizons of the studied soils in dependence to the fraction size

Horizon index and depth, cm	Aggregate porosity, % in dependence to the fraction size, mm					
	7–5 mm	5–3 mm	3–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm
Soil and land use type						
Chestnut, calcareous, middle loamy soil; long-term fallow land (desert steppe, Kizilyurt district)						
A 5–15	37.8	34.7	31.4	32.3	31.9	32.3
B_1 21–34	31.8	30.1	29.4	28.4	28.5	30.1
B_2 35–45	31.7	31.2	29.8	29.9	29.7	31.0
C_1 46–65	31.3	31.3	30.8	31.0	31.4	31.6
Chestnut, calcareous, light loamy soil; arable land (wheat, Kizilyurt district)						
A_{plow} 0–20	38.5	37.1	34.6	32.0	30.7	30.7
Meadow–chestnut, slightly solonetzic, heavy loamy soil; long-term fallow land (a former alfalfa field, Khasavyurt district)						
A 6–28	33.3	34.1	31.2	30.3	29.5	28.2
B_1 29–60	30.6	30.3	29.5	28.7	28.8	28.5
C_1 72–150	28.4	28.3	27.8	27.3	27.5	28.8

tions up to 7–5 mm in size. Interestingly, the aggregate porosity in the C_1 horizon drops to almost identical values that are close to the computed close-packed porosity (a method involving mutual coupling of mineral particles in a clastic rock). Apparently, this approximation to the computed porosity is determined by the high content of dusty particles in the mechanical and especially microaggregate composition.

In chestnut soils, the parameter value is not so close to the computed value; it varies in the range of 28–31%. Therefore, the porosity of aggregates in lower horizons virtually does not depend on their size. In the chestnut soil (field of wheat), the porosity of large aggregates is slightly higher.

Analysis of aggregate porosity estimated based on the percentage content of fractions (Table 3) shows

Table 3. Weighted aggregate porosity in various horizons of the studied soils

Horizon index and depth, cm	Aggregate porosity computed based on the percentage content of fractions						Total porosity, %	Total aggregate porosity, %	Interaggregate porosity, %
	size of aggregate fractions, mm								
	<5	5–3	3–2	2–1	1–0.5	<0.5			
Soil and land use type									
Chestnut, calcareous, middle loamy soil; long-term fallow land (desert steppe, Kizilyurt district)									
A 5–15	13.1	3.9	3.3	6.5	1.5	6.1	49.0	34.0	15.0
B_1 21–34	8.8	8.8	5.3	4.6	0.7	1.8	51.0	30.0	21.0
B_2 35–45	15.0	5.6	4.6	3.6	0.9	1.4	49.0	31.0	18.0
C_1 46–65	15.3	4.4	3.1	3.5	1.5	3.6	45.0	31.0	14.0
Chestnut, calcareous, light loamy soil; arable land (wheat, Kizilyurt district)									
A_{plow} 0–20	15.0	2.0	1.8	4.2	2.1	5.4	56.0	32.0	22.0
Meadow–chestnut, slightly solonetzic, heavy loamy soil; long-term fallow land (a former alfalfa field, Khasavyurt district)									
A 6–28	16.3	3.6	2.7	4.3	1.0	4.0	54.0	32.0	22.0
B_1 29–60	20.5	5.6	2.1	1.5	0.2	0.4	49.0	30.0	17.0
C_1 72–150	20.5	5.6	2.1	1.5	0.2	0.4	49.0	30.0	17.0

that the majority of interaggregate porosity is attributed to large aggregates.

CONCLUSIONS

The withdrawal of lands from intense agricultural use and their transformation into fallow lands result in a gradual improvement of their agrophysical properties and restoration of the native environmental–genetic state of soils.

The results convincingly demonstrate that the porosity of aggregates is closely linked to their composition, structure, and origin, as well as to the general soil genesis. The physical properties of soils are an important factor that determines their fertility. Even though physical properties do not provide nutrients to plants, they still affect their development. Therefore, it is imperative to understand and know how to regulate the agrophysical parameters of soils. This knowledge is essential for reproduction of soil fertility and productivity of agricultural crops.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflicts of interest.

Statement on the welfare of humans or animals. This article does not contain any studies involving animals performed by any of the authors.

REFERENCES

Currie, J.A., Gaseous diffusion in aeration of aggregated soils, *Soil Sci.*, 1961, vol. 92, pp. 40–45.

Currie, J.A., Diffusion within soil macrostructure: a structural parameter for soils, *Soil Sci.*, 1965, vol. 16, pp. 279–289.

Currie, J.A., The volume and porosity of soil crumbs, *Soil Sci.*, 1966, vol. 17, pp. 24–35.

Dospekhov, B.A., *Metodika polevogo opyta (s osnovami statisticheskoi obrabotki rezul'tatov issledovanii)* (Method of Field Experiment with Principles of Statistical Data Processing), Moscow: Agropromizdat, 1985.

Kachinskii, N.A., *Struktura pochvy* (The Soil Structure), Moscow: Mosk. Gos. Univ., 1963.

Kachinskii, N.A., *Fizika pochvy* (Soil Physics), Moscow: Vysshaya Shkola, 1965, part 1.

Kushnarev, A.S. and Pogrelyi, V.V., Choose of soil tillage methods, *Tekh. APK*, 2008, no. 1, pp. 17–21.

Lebedeva, I.I., Koroleva, I.E., and Grebennikov, A.M., The evolutionary concept of chernozems in agroecosystems, *Byull. Pochv. Inst. im. V.V. Dokuchaeva*, 2013, no. 41, pp. 16–26.

Morkovkin, G.G. and Demina, I.V., The influence of green manure and fallow land on the fertility dynamics of leached chernozems in the moderately arid and kolkis steppe of the Altai krai, *Vestn. Altaisk. Gos. Agrar. Univ.*, 2011, no. 11 (85), pp. 18–22.

Shevlyagin, A.I., Soil density as one of conditions of its fertility, *S-kh. Proizvod. Sib. Dal'nego Vost.*, 1963, no. 3, pp. 43–44.

Slesarev, V.N., Influence of the structure of the arable layer on fertility and productivity in grain-fallow crop rotation, in *Puti povysheniya urozhainosti zernovykh kul'tur v Zapadnoi Sibiri* (The Yield Increase of Grain Crops in Western Siberia), Omsk: Omsk. S-kh. Inst., 1984, pp. 9–13.

Tabatabai, M.A. and Hanway, J.J., Some chemical and physical properties of different-sized natural aggregates from Iowa soils, *Soil Sci. Soc. Am. J.*, 1968, vol. 32, pp. 588–591.

Teimurov, S.A., Assessment of fertility on different-level areas of pastures in arid conditions of Dagestan, *Gorn. Sel. Khoz.*, 2019, no. 2, pp. 36–43.

Teimurov, S.A., Imasheva, S.N., and Babaev, T.T., Influence of types of fertilizers on the change of the physical properties of the meadow-chestnut soil of the Terek-Sulak valley, *Zemledelie*, 2020, no. 5, pp. 16–22.

Terpelets, V.I. and Slyusarev, V.N., *Uchebno-metodicheskoe posobie po izucheniyu agrofizicheskikh i agrokhimicheskikh metodov issledovaniya pochv* (Practical Manual for Analysis of Agrophysical and Agrochemical Properties of Soils), Krasnodar: Kuban. Gos. Agrar. Univ., 2010.

Vadyunina, A.F., *Metody issledovaniya fizicheskikh svoistv pochv* (Manual for Analysis of Physical Properties of Soils), Moscow: Agropromizdat, 1986.

Vershinin, P.V., *Pochvennaya struktura i usloviya ee formirovaniya* (Formation of Soil Structure), Moscow: Akad. Nauk SSSR, 1958.

Wittmuss, H.D. and Mazurak, A.P., Physical and chemical properties of soil aggregates in a brunizem soil, *Soil Sci. Soc. Am. J.*, 1958, vol. 22, pp. 1–5.

Zakharov, S.A., Classification of Caucasian soils by historical, geographic, and genetic principles, in *Yubileinyi sbornik, posvyashchennyi 70-letiyu professora S.A. Zakharova* (Jubilee Collection of Scientific Research Works Dedicated to the 70th Anniversary of Prof. S.A. Zakharov), Kharkov: Khark. Gos. Univ., 1954, pp. 1–38.

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