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THE INHOMOGENEITY OF THE PHYSICAL PROPERTIES OF ARABLE CHERNOZEMS THROUGH THE CONCEPT OF AGROGENIC PEDOGENESIS

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Abstract. *The inhomogeneity of the physical state of soils is examined as a complex form of agrogenic degradation of arable chernozems. From the perspective of this concept, the key element of the inhomogeneity of the physical state of arable chernozems is considered to be the degradation of the chernozem aggregate structure associated with dehumification materialized in the reduction of the self-regulation, self-reproduction, and self-organization capacity of the physical subsystem of chernozems. This entails two opposite genetic-evolutionary trends - aridic and neohydromorphic - of the evolution of arable chernozems. In arable chernozems, the physical state of the soils determines the meaning and intensity of chernozem typogenetic processes and the ratio between these and the agrogenetic processes induced by the inclusion and use of chernozems in the agricultural regime. The degradation of the physical state of soils leads to significant changes in the pedogenetic and pedofunctional regimes and involves the disruption of the relationships and interactions between native and agrogenic processes, materialized in the reduction of the self-production capacity of chernozem pedogenesis and the development of a new form of degradation - the spatial non-homogeneity of the physical state of arable chernozems. Seasonal overwetting is replaced by periodic overwetting (moistened chernozem soil) and subsequently permanent with permanent overwetting (wet chernozem and chernozemoid soils).*

Keywords*: arable chernozems; agrogenic degradation; soil physical inhomogeneity.*

INTRODUCTION

The evolution of arable chernozems within the current stage of anthropo-natural chernozem pedogenesis is primarily determined by the physical state of the soils (Jigău et al., 2022). In this context, our research has shown that the unfavorable physical state of arable chernozems is the main factor that limits the realization of their reproductive potential even within agricultural technologies oriented towards supporting and regenerating the chernozem pedogenesis process.

In this chapter, numerous studies have shown that physical degradation processes manifest themselves at all levels of structural-functional organization of the soil ecosystem and materialize in unfavorable changes in the structural-aggregate composition, compaction-settlement-slitting of the soil mass, changes in the qualitative and quantitative characteristics of the porous space, the decrease in the main types of capacity (total, field, etc.) for water, its permeability and hydraulic conductivity (Jigău, Leşanu, 2012). All this leads to the degradation of physical fertility factors which, in addition to the direct impact on the degree of water, air,

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heat supply of the soil and agrophytocenoses, also have an indirect impact on the degree of mobility and accessibility of nutrients.

Their uneven realization in space, both vertically (in profile) and laterally, led to the development of a new form of agrogenic degradation - the spatial heterogeneity of physical properties and regimes, becoming one of the key forms of agrogenic degradation of arable chernozems. The main factor causing this form of degradation is the intensive and frequently irrational agricultural use based on soil works and the practice of a fertilization system incompatible with the pedogenetic process of solification, which was indicated as early as the late 19th and early 20th centuries by P.A. Costacev and Eugen N. Giurgea (Costacev et al., 1884). In this sense, it is unanimously recognized that while native chernozems, with few exceptions, are characterized by a high degree of homogeneity of basic physical properties (structural-aggregate composition, apparent density, total and differential porosity), agricultural use has led to the establishment of a stable trend of non-homogenization in time and space in arable chernozems (Jigău et al., 2012). This is intensified by the spatial overlap with the elements of natural non-homogeneity caused by the particularities of geomorphological conditions and parental deposits. This has led to the development, over time, of a mosaic soil cover with pedogenetic (hydric, thermal, aeration) and pedofunctional (aerohydric, hydrothermal) regimes.

Through this prism of ideas, the spatial inhomogeneity of the physical properties of arable chernozems is already a factor with an important impact that redistributes pedogenetic resources (heat, humidity) materialized in the inhomogeneity of pedogenetic and pedofunctional processes and, respectively, in the meaning and intensity of pedogenetic processes, even within small spaces.

Despite this fact, the spatial inhomogeneity of agricultural soil properties has come to the attention of research and decision-makers relatively recently with the development of the concept of precision agriculture. This uses geostatistical and multivariate techniques to manage spatial variability and has emerged as an essential tool in addressing the current challenge faced by contemporary agriculture (Shukla et al., 2004).

However, in this case too, it is approached simplistically through the prism of mineral fertilization in the context of reducing fertilizer costs. In this sense, we mention that the attempts undertaken will not ensure the goals and results by promoting precision agriculture because the heterogeneity of physical properties is the main factor limiting the efficiency of mineral fertilization. At the same time, more recent research has shown that the increased heterogeneity of physical/agrophysical properties is the main factor leading to significant variability in crop yields. In addition, both traditional and alternative technologies that do not take into account the heterogeneity of physical properties do not ensure the optimization of crop conditions across the entire field.

In addition, the evolutionary trend induced by the inhomogeneity of the physical state has already transformed chernozems into less stable and less fertile soils. The unidirectional achievement of such an evolution implies the degradation of the chernozem process as a type of pedogenesis (Jigau et al., 2023).

In this context, in the present work, the spatial inhomogeneity of physical properties is examined through the prism of the impacts and genetic-evolutionary aspects induced by it in the evolution of chernozems, and the achievement of this objective implied the need to evaluate the factors and mechanisms that determine it within an integrated concept based on the theory of chernozem pedogenesis.).

MATERIAL AND METHODS

The conceptual-methodological framework of the present research is provided by the concept of the priority role of the physical state of the soil in the achievement and reproduction of the chernozem process of solification, according to which the physical state of the soil is responsible for the pedogenetic and pedofunctional regimes that determine the meaning and intensity of chernozem typogenetic processes. At the same time, the physical state of the soil determines the weight of the ratio between the chernozem typogenetic processes (humus formation-accumulation and aggregation-structuring manifested in biogenic accumulation) and the secondary ones (leaching, eluviation, carbonate migration, illuviation, etc.), responsible for the migration and differentiation of substances on the soil profile materialized in the differentiation of chernozems at the subtype level.

In arable chernozems, the physical state of the soils determines the meaning and intensity of chernozem typogenetic processes and the ratio between these and the agrogenetic processes induced by the inclusion and use of chernozems in the agricultural regime.

The degradation of the physical state of soils leads to significant changes in the pedogenetic and pedofunctional regimes and involves the disruption of the relationships and interactions between native and agrogenic processes, materialized in the reduction of the self-production capacity of chernozem pedogenesis and the development of a new form of degradation - the spatial non-homogeneity of the physical state of arable chernozems.

Through this prism of ideas in our research, the non-homogeneity of the physical state of arable chernozems is examined as a complex agrogenic form of their degradation manifested in the intensification of the variability of the physical parameters (structure, apparent density, volume and composition of the pore space, humidity), hydrophysical and biological parameters related to these in space and time. This is determined exclusively by the processes induced by agrogenesis and overlaps in space with the genetic-functional inhomogeneity and leads to the intensification of the degree of inhomogeneity of the soil cover materialized in the inhomogeneity of the pedogenetic (hydric, thermal, aeration) and pedofunctional (aerohydric, hydrothermal, oxidation-reduction, biological) regimes and leads to the modification of the meaning and intensity of pedogenetic processes (Jigau et. al. 2024; Cherkasov et al., 2011).

The main agrogenic factors that determine it are primarily soil works, especially works that involve disturbing the natural composition of soils, especially the humus-accumulative horizon that determines the entire complex of processes of evolution of chernozems in agricultural regime.

In this sense, our previous research has shown that the inclusion of chernozems in the region in active agricultural use is accompanied by changes at all levels of structural-functional organization of the soil substance.

In this sense, it has been established that under conditions when, apparently, their profile preserves the basic features characteristic of chernozems, over time, significant changes occur in the soils both in their morphological and morphogenetic properties:

1. Transformation of the humus profile, manifested by changes in the color, thickness of the content and quality of the humus.
2. Transformation of the carbonate profile, manifested by changes in the depth, shapes and character and migration of newly formed carbonates. In this regard, it was established that the thickness of the carbonate fluctuation layer increases during the year depending on the climatic conditions of the year, the physical state of the soils and its annual dynamics.
3. Formation of neohorizons of anthropogenic origin: arable and subarable horizons.

The arable horizon includes the layer with the highest frequency of mechanical mixing of the soil substance through their cultivation and the highest pressure of substances (mineral and organic fertilizers) of non-pedogenetic origin. In most cases, it has a stratified arrangement manifested in the indicators of the state of arrangement (apparent density, total differential porosity) and structural-aggregate composition. Frequently, it is partially depleted in fine clay as a result of its eluvium with the downward currents of water in the underlying layer or as a result of deflationary desilting or water erosion. Depending on the meaning and intensity of the processes that take place in it, which are inevitably dependent on the spatial inhomogeneity of the physical state, the arable horizon can be agrochernozem, agroumbric, agroocric, agrocompacted, arpodestructured, agrostructured, agrodesargillized, agrometamorphized, groturlational, agrobrazional, agroselitoge (Lesanu et al., 2012).

The subarable horizon is distinguished by higher values of apparent density, nuciform-prismoid structure, reduced content of agronomically valuable aggregates (0.25-10 mm), significant reduction of the total volume of pores and that of interaggregate pores. At the same time, a significant reduction of moisture-conducting pores and an increase in the volume of moisture-protective pores are attested. In the composition of the latter, the volume of pores occupied by physically bound water increases.

The physical state of the subarable horizon is influenced to a small extent by pedogenetic processes and to a greater extent by processes induced by mechanical pressures exerted by soil tillage aggregates. In our research, these, depending on the physical state, are divided into deformed/disturbed, consolidated, hardpanized, and depending on the structural-aggregate composition, we propose to distinguish boulder, prismatic, prismoid, polygonal, nut-shaped and columnoid horizons (Lesanu et al., 2012; Jigau et al., 2014).

A specific feature of the physical state of the agrogenic layer (arable horizon + subarable horizon) is the formation of pseudoaggregates of agrogenic origin that differ from natural ones in shape and higher density.

Research conducted in the last 10-15 years within 12 pedogeographical districts in the area between the Prut and Dniester rivers has shown that the agrogenic degradative effects that cause the spatial inhomogeneity of the physical state of soils are relatively similar in nature given that they are determined by the same anthropogenic factors.

Agrogenic pedogenesis is accompanied by the disaggregation of the native chernozem structure in the agrogenic layer and the reorganization of the integration and organization model of the soil mass and leads to the modification of the structural-aggregate composition of the soil.

Under conditions of unidirectional dehumification trend and stability of the granulometric composition, especially the content of particles <0.005 mm, the reaggregation of the soil mass is achieved with the formation of aggregate formations with a lower humus content (corresponding to its content in soils) that only partially neutralize the adsorption potential of particles < 0.005 mm. Therefore, the C:∑<0.005 mm ratio presents values lower than the optimal ones. Therefore, agronomically valuable agrogenic aggregates (0.25-10 mm) are characterized by an advanced degree of vulnerability to disaggregation under the action of water.

Through this prism of ideas, the current state of arable chernozems implied the need for an evaluation of the multilateral action of the physical/agrophysical state of the soil on the biological processes that take place in it in their capacity as a driving force of the direction and intensity of the chernozem process of solification.

In this sense, it is well known that physical/agrophysical properties play a decisive role in agrocenotic metabolism, determining the rate of biogeochemical cycles, the activity of soil biota and the processes of transformation of matter and energy. At the same time, physical/agrophysical properties determine the rate and nature of plant root system development, the availability and use of nutrients, the formation of underground and aboveground phytomass and crop yield (Jigau et al., 2015).

In this sense, the specified researches have shown that the crops, especially their structure and rotation, in turn, significantly influence the physical/agrophysical properties of arable chernozems and the water balance of the agroecosystem, these being closely influenced by the mass and structure of the aboveground organs of agricultural plants, by the mass and structure of the root systems, by their distribution throughout the soil profile and by the technology of cultivating the crops.

In this sense, it is known that the ecosystem role of the physical properties of the soil involves ensuring favorable conditions for the vital activity of various groups of microorganisms participating in the processes of mass and energy transfer and transformation of organic matter in the soil. Hydrostable aggregates account for about 81.3% in determining the community of soil bacillary organisms, about 70.5% of the organisms using mineral nitrogen and cellulosic microflora. Porosity is the factor whose share in the development of bacilli is 92.6% and that of fungi is 77.6%. The share of apparent density in the development of the activity of microorganisms that use mineral nitrogen is about 80.7%, of cellulolytic microorganisms 52.6% and of bacilli 55.8% (Prudnicova, 2004).

From the perspective of the unity of biological and physical processes within the biophysical genesis of chernozems, physical degradation inevitably leads to the reduction of biological activity in its quality with an extremely important role in the aggregation-structuring of the soil mass. In this sense, from the perspective of current concepts of the aggregation-structuring process, living organisms act as primary agents in the formation of the soil structure by associating mineral particles into structural aggregates.

Through this prism of ideas, biota transforms organic matter, forms humic substances and mechanically restructures the soil mass, ensuring porosity and aggregate hydrostability. Thus, the structuring of the soil mass represents a bioroutine process in which living organisms form the physical matrix of the soil, determining the aerohydric regime of the soil and, respectively, the meaning and intensity of the chernozem typogenetic processes.

At the same time, however, from the moment of the inclusion of chernozems in the agricultural circuit, their biota undergoes significant changes, including a sudden reduction in the number or complete disappearance of many species of microorganisms associated with certain agricultural crops. Their place is taken by microorganisms that are not specified for soil formation processes and effective interactions with plants. Plant roots are colonized with non-specific microorganisms, which, consequently, perform atypical functions materialized in their parasitism on the plant organism (Sincovscaia et al., 2012).

As a result, practically all arable chernozems are affected by overcultivation, which manifests itself in the reduction of the self-reproduction capacity of the soil ecosystem and the redistricting of processes in directions determined by abiotic factors manifested in the opposite control processes - aridification and secondary neohydromorphization depending on the specific landscape conditions (Jigau et al., 2015).

RESULTS AND DISCUSSIONS

Text Through the concept of quantitatively and qualitatively interdependent and interdetermined interaction of the humification process and the aggregation-structuring process, the genetic-evolutionary system [humic system]↔[aggregate system] represents a continuum that assumes the simultaneous or certain seasonal consecutive realization of physical, biological and physico-chemical processes, part of which is oriented towards disaggregation/deterioration and another towards the formation of structural aggregates.

In the natural regime, within the annual cycle of functioning of the physical system of chernozems, the processes of deterioration-formation/aggregation-structuring tend towards equilibrium, which maintains the structural-aggregate state of the soil in a relatively stable equilibrium. In this sense, the aggregation and disaggregation of the soil mass implies its renewal (reaggregation) in the composition of aggregates in situ. By its essence, this mechanism implies the permanent compensation within the aggregates of the quantities of humus, annually consumed during mineralization with quantities of freshly formed humus.

The intensity and duration of reaggregation in the natural regime depends on the bioclimatic conditions of the year and the specific landscape conditions and are indicators of the degree of stability of the aggregate structure of soils. Therefore, the latter is an integrative index of the degree of stability of the physical system of the soil.

In agricultural regime, the dynamics of the structural-aggregate state of soils is influenced directly by soil tillage and frequent field passes or indirectly by the impact on soil biota through mineral fertilization and plant protection works. Their permanent impact, with different frequency and intensity depending on the agricultural system practiced, has led to a reduction in the self-regulation, self-reproduction and self-organization capacity of the physical system of the soil manifested in the unidirectional destructuring of the soil mass.

In this regard, the data presented in Tab. 1 indicates an advanced degree of spatial variability of the structural-aggregate composition both vertically and horizontally within a transect with a length of 10 m and a measurement step of 2 m.

In this context, we draw attention to the high degree of variability of the structural-aggregate composition and the detachment of the values of the qualitative-functional structural parameters in the uncompacted and compacted spaces, these significantly detaching from the respective parameters within the control variant (forest strip) (Tab. 1, 2).

The comparative analysis of the structural-aggregate parameters of arable chernozems and uncultivated forest strips shows that within arable lands the structural aggregation processes are determined, exclusively, by the agrogenetic impact. This is also indicated by the ratio between the contents of the structural aggregate fractions (Tab. 3).

This implies the conclusion that the soil mass reaggregation processes within the annual cycle are significantly different from those of uncultivated chernozems (forest strip).

Table 1

Spatial variability of the structural-aggregate composition of typical weak humiferous clayey loam chernozem on clayey loam

Point	Variant	Depth, cm	Fractionation method	Aggregate diameter, mm. Aggregate content, %								
				>10	10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25	<0,25
1	Netas	0-15	dry	12,1	5,3	6,4	21,6	25,3	16,3	3,8	2,4	6,8
			wet	-	-	1,06	5,3	22,30	21,28	8,00	15,50	26,58
		25-35	dry	25,0	10,7	10,5	12,3	7,3	14,0	5,5	5,7	9,0
			wet	-	-	-	2,80	3,02	9,14	10,76	16,34	57,88
		40-55	dry	16,2	11,6	10,7	19,6	17,7	1,6	2,7	1,9	3,0
			wet	-	-	-	1,10	3,34	15,52	13,94	18,50	47,60
		60-70	dry	30,0	14,8	9,8	10,8	9,0	13,4	3,6	3,0	5,6
			wet	-	-	-	1,1	1,0	6,0	9,2	18,2	63,9

	Tamping	0-15	dry	11,9	6,5	6,1	9,2	14,9	23,5	6,3	10,9	10,7
			wet	-	-	-	0,78	3,78	8,12	9,48	19,32	58,52
		25-35	dry	16,5	11,3	9,9	12,8	10,2	19,1	4,5	6,2	9,5
			wet	-	-	-	1,10	10,12	10,04	9,46	10,70	58,58
		40-55	dry	16,2	12,6	9,6	23,3	15,6	13,3	2,7	2,7	9,0
			wet	-	-	-	1,06	2,52	12,80	11,54	16,86	55,22
		60-70	dry	4,9	11,0	8,1	15,3	18,8	23,6	3,90	5,4	9,0
			wet	-	-	-	1,80	4,92	13,30	10,98	14,78	54,22
2	Netas	0-15	dry	11,2	6,3	6,5	21,8	25,0	16,3	3,6	2,6	13,2
			wet	-	-	-	6,9	22,25	21,38	8,60	15,50	25,77
		25-35	dry	24,2	9,7	10,8	12,3	7,3	14,3	5,6	5,6	10,2
			wet	-	-	-	3,00	5,02	9,41	10,67	16,53	55,37
		40-55	dry	10,61	10,6	4,7	19,8	17,3	2,6	2,1	1,7	21,0
			wet	-	-	-	2,00	2,34	16,25	13,49	18,90	47,02
		60-70	dry	29,9	13,41	8,8	7,4	6,9	16,0	4,1	9,4	4,1
			wet	-	-	-	-	2,20	9,80	9,20	19,80	59,0
	Tamping	0-15	dry	17,9	5,8	6,4	10,2	14,8	22,4	6,0	10,3	17,4
			wet	-	-	-	1,12	10,21	6,21	9,28	19,23	53,95
		25-35	dry	13,6	14,3	8,9	13,3	9,9	20,4	6,3	6,2	7,1
			wet	-	-	-	-	8,00	9,14	12,67	16,35	53,84
		40-55	dry	12,0	11,6	10,4	23,0	16,5	13,3	8,0	10,9	4,3
			wet	-	-	-	1,43	2,32	16,52	14,39	19,80	45,54
		60-70	dry	9,9	10,1	8,1	13,5	19,8	23,3	4,3	4,5	6,8
			wet	-	-	-	2,80	5,29	13,47	12,86	3,19	62,39
3	Netas	0-15	dry	13,5	8,9	7,8	16,3	19,6	20,0	4,9	5,6	3,4
			wet	-	-	-	2,60	3,86	23,50	9,62	9,58	50,84
		25-35	dry	27,3	10,4	11,5	10,3	9,6	21,9	4,2	4,8	3,0
			wet	-	-	-	1,16	4,29	20,18	9,16	13,30	51,91
		40-55	dry	31,5	9,6	10,4	9,3	6,9	18,1	5,5	6,0	2,7
			wet	-	-	-	2,61	4,30	19,90	10,58	14,06	48,55
		60-70	dry	30,9	10,1	10,7	6,0	6,6	20,3	5,2	6,3	3,9
			wet	-	-	-	-	5,28	23,96	14,38	16,82	39,56
	Tamping	0-15	dry	21,8	12,1	10,5	9,3	11,5	21,3	5,3	5,6	2,6
			wet	-	-	-	-	3,46	24,9	18,12	19,26	34,29
		25-35	dry	32,5	16,0	12,4	8,3	8,11	14,0	3,3	4,0	1,4
			wet	-	-	-	-	2,08	23,40	16,19	19,56	38,77
		40-55	dry	36,9	14,3	8,8	8,9	9,6	16,3	1,4	2,0	1,8
			wet	-	-	-	-	1,86	24,39	19,38	18,42	35,95
		60-70	dry	29,3	12,9	18,3	9,9	8,1	20,3	1,8	2,2	2,2
			wet	-	-	-	-	3,94	26,58	18,39	19,98	31,11
4	Forest strip	0-15	dry	8,1	11,8	8,3	23,3	13,3	18,8	6,0	6,3	4,1
			wet	-	-	-	0,58	1,88	1,10	8,04	13,62	74,78
		25-35	dry	10,8	13,0	13,7	19,9	12,0	17,2	8,3	2,9	2,2
			wet	-	-	-	3,78	7,88	9,58	11,40	4,88	45,88
		40-55	dry	11,0	16,5	15,5	21,5	11,3	12,8	2,6	3,9	4,9
			wet	-	1,42	3,42	1,1	1,16	5,72	10,40	20,78	56,3
		60-70	dry	14,0	16,6	11,0	19,2	12,6	21,6	9,7	6,2	3,1
			wet	-	1,20	0,60	1,80	1,80	7,80	11,00	22,8	53,2

Table 2.

Spatial inhomogeneity of the qualitative and functional structural parameters of typical weakly humiferous clayey loam arable chernozem on clayey loam

Point	Variant	Depth, cm	Qualitative-functional structural parameters				
			Content of valuable organic aggregates (0.25-10 mm), %	Content of agronomically valuable aggregates (5-0.25 mm), %	Content of chernozem aggregates (3-1 mm), %	Structuring coefficient	Criterion of hydrostability
1	Netas	0-15	81,1	69,4	41,6	4,3	380
		25-35	66,0	44,8	21,3	1,9	241
		40-55	80,8	43,5	19,3	4,2	70,5
		60-70	64,4	39,8	22,4	1,8	263
	Tamping	0-15	77,4	64,8	38,4	3,4	167
		25-35	74,0	52,8	31,3	2,8	188
		40-55	74,8	57,6	28,9	3,0	525

		60-70	86,1	53,8	42,4	6,2	277
2	Netas	0-15	75,6	69,3	41,3	3,1	389
		25-35	65,6	45,1	21,6	1,9	243
		40-55	60,4	43,5	19,9	1,5	852
		60-70	66,0	43,8	22,9	1,9	215
	Tamping	0-15	64,7	63,7	37,2	1,83	174
		25-35	79,3	56,1	30,3	3,8	232
		40-55	83,7	71,7	29,8	5,1	181
		60-70	83,3	65,4	43,1	5,	182
3	Netas	0-15	83,0	66,4	39,6	4,9	183
		25-35	69,7	50,5	31,5	2,3	250
		40-55	65,8	45,8	25,0	1,9	214
		60-70	65,2	44,4	26,9	1,9	271
	Tamping	0-15	75,6	53,0	32,8	3,1	342
		25-35	66,1	37,7	22,1	2,0	490
		40-55	61,3	36,2	26,9	1,6	1111
		60-70	68,5	42,3	28,4	2,2	944
4	Forest strip	0-15	87,8	67,7	32,1	7,2	180
		25-35	87,0	60,3	25,2	6,7	145
		40-55	85,1	52,1	24,1	5,4	480
		60-70	82,9	68,6	34,2	4,8	211

Table 3.

Variability of the content of structural aggregate fractions as an indicator of the spatial inhomogeneity of the physical state of soils

Point	Variant	Depth, cm	Aggregate diameter, mm							
1	Netas	0-15	>2	>3	>1	>10	>5	>7	>0,5	>0,25
		25-35	>10	>1	>3	>7	>5	>2	>0,25	>0,5
		40-55	>3	>2	>10	>7	>5	>0,5	>0,25	>1
		60-70	>10	>7	>1	>3	>5	>2	>0,5	>0,25
	Tamping	0-15	>1	>2	>10	>0,25	>3	>7	>0,5	>5
		25-35	>1	>10	>3	>7	>2	>5	>0,25	>0,5
		40-55	>3	>2	>1	>7	>10	>5	>0,5	>0,25
		60-70	>1	>2	>3	>7	>5	>0,25	>10	>0,5
2	Netas	0-15	>2	>3	>1	>10	>5	>7	>0,5	>0,25
		25-35	>10	>1	>3	>5	>7	>2	0,5	0,25
		40-55	>3	>2	>5	7	10	>1	>0,5	>0,25
		60-70	>10	>2	>1	>7	>0,25	>5	>3	>0,25
	Tamping	0-15	>1	>10	>2	>0,25	>3	>5	>0,5	>7
		25-35	>1	>7	>10	>3	>2	>5	>0,5	>0,25
		40-55	>3	>2	>1	>10	>7	>0,25	>5	>0,5
		60-70	>1	>2	>3	>7	>10	>5	>0,25	>4,3
3	Netas	0-15	>1	>2	>3	>10	>7	>5	>0,25	>0,5
		25-35	>10	>1	>5	>7	>3	>2	>0,25	>0,5
		40-55	>10	>1	>5	>7	>3	>2	>0,25	>0,5
		60-70	>10	>1	>5	>7	>2	>0,25	>3	>0,5
	Tamping	0-15	>10	>1	>7	>2	>5	>3	>0,25	>0,5
		25-35	>10	>7	>1	>0,5	>3	>2	>0,25	>5
		40-55	>10	>1	>7	>2	>3	>5	>0,25	>0,5
		60-70	>10	>1	>5	>7	>3	>2	>0,25	>0,5
4	Forest strip	0-15	>3	>1	>2	>7	>5	>10	>0,25	>0,5
		25-35	>3	>1	>5	>7	>2	>10	>0,5	>0,25
		40-55	>3	>7	>5	>1	>2	>10	>0,25	>0,5
		60-70	21,6	>3	>7	>10	>2	>5	>0,5	>0,25

In this regard, our previous research has shown that the deterioration of structural aggregates increases the contact surface of the soil mass with mineralizing agents (mineralizing microorganisms), and the access of oxygen to the organic matter previously protected in the aggregates. Increased aeration contributes to the increase in the biological activity of microorganisms and leads to the accumulated mineralization (decomposition) of humus.

At the same time, the deterioration of aggregates > 3 mm leads to the formation of aggregates with dimensions < 1 mm (1-0.25 and < 0.25 mm) which are easily subject to wind erosion (eolian erosion) or water (water erosion thus removes significant amounts of humus contained in them from the soil). According to our calculations, fine aggregates (1-0.25 mm) and microaggregates contain more than 25-30% of the total reserves contained in the soil.

According to the concept of the hierarchy of soil structural organization levels, the aggregate level is formed within the pedogenesis process through the interaction of elementary particles that led to the formation of microaggregates, aggregates and neoformations characteristic of chernozems and each of their subtypes (Shukla et al., 2004; Voronin, 1984).

By its essence, the structural-aggregate level represents the primary stage of spatial organization of the solid phase of the soil, inherited, to a large extent, from the parent rock and transformed-shaped by the processes of solification.

Through this prism of ideas, the aggregate level determines the formation and functioning of the upper levels of structural-functional organization-horizon profile-soil cover (Holodov et al., 2019; Umarova et al., 2021).

In this sense, any change within the aggregate level inevitably leads to changes in the higher levels.

In this context, the deterioration of the structure of arable chernozems is the key factor that involves the development of spatial inhomogeneity of their physical state. This process, over time, transfers the soil cover from a homogeneous state to an inhomogeneous state within which neighboring microspaces can be cardinally distinguished from each other by their basic physical properties (Tab. 4).

The main forms of spatial inhomogeneity of the physical state of arable chernozems are determined by the degradation of the structure:

1 Inhomogeneity of the settlement state: Structural deterioration leads to inhomogeneous compaction of the agrogenic layer both vertically (manifested in its stratification into substrates with apparent density varying in large intervals), including up to values corresponding to hardpan (>1.45 g/cm3) (Tab. 4).

2. Consolidation of the soil mass. The degradation of the agronomically valuable chernozem structure (0.25-10 mm), especially the lumpy-grained one (7-1 mm), leads to "dusting of the structure" manifested in the increase in the content of 2-0.25 mm aggregates and microaggregates (<0.25 mm), leading to the creation in the arable layer of extremely contrasting physical states upon wetting (paste state) and drying (slitter state) which favor the formation of aggregates >10 mm and a relatively high share of 0-7 mm aggregates. When moistening in such horizons, predominantly anaerobic conditions are established in the soil, which favor anaerobic processes, in particular the mobilization of iron, and when drying, consolidation with the formation of microcracks (aeration porosity >25%) through which accelerated evaporation of soil water occurs, manifested in the aridification of the agrogenic layer (Tab. 4) (Cust et al., 2010).

Table 4.

Spatial variability of the settlement state index of typical weakly humiferous arable chernozem, clayey loam on clayey loam

Point	Variant	Depth, cm	Physical parameters					
			humidity		humidity	porosity, %		
			% g/g	% V/V		total	occupied by water	aeration
1	Netas	0-15	14,8	19,2	1,1	60,8	19,2	41,6
		25-35	23,7	28,4	1,2	53,6	28,4	25,4
		40-55	13,1	17,0	1,3	50,9	17,0	33,9
		60-70	12,9	16,8	1,3	51,5	16,8	34,7
	Tamping	0-15	17,6	26,4	1,5	40,0	26,4	13,6
		25-35	12,1	16,9	1,4	45,1	16,9	28,2
		40-55	14,2	19,9	1,4	46,1	19,9	26,2
		60-70	9,1	11,7	1,3	51,5	11,7	39,8
2	Netas	0-15	15,1	16,0	1,06	58,4	16,0	42,4
		25-35	21,9	25,2	1,15	54,9	21,9	33,9
		40-55	18,8	23,1	1,23	52,1	23,1	29,0
		60-70	16,3	22,2	1,36	51,3	22,2	29,1
	Tamping	0-15	14,9	19,5	1,31	49,0	19,5	29,5
		25-35	12,8	18,2	1,42	45,4	18,2	27,2
		40-55	14,3	20,9	1,46	44,90	20,9	24,0
		60-70	9,4	14,3	1,52	43,1	14,3	28,8
3	Netas	0-15	16,1	16,4	1,02	60,0	16,4	43,9
		25-35	23,8	26,4	1,11	56,8	26,4	30,4
		40-55	19,4	24,4	1,26	51,5	24,4	27,1
		60-70	17,8	23,1	1,30	51,3	23,1	28,2
	Tamping	0-15	13,2	16,9	1,28	50,2	16,9	33,3
		25-35	17,8	24,7	1,39	46,5	24,7	21,8
		40-55	13,3	19,4	1,46	45,3	19,4	25,9
		60-70	8,4	12,8	1,52	43,1	12,8	30,3
Forest strip		0-15	16,4	19,7	1,20	52,5	19,7	32,3
		25-35	15,1	21,1	1,24	55,1	21,1	34,0
		40-55	15,7	18,8	1,20	53,8	18,8	35,0
		60-70	12,1	16,9	1,20	57,8	16,9	40,9

An indicator of arid degradation is the frequency and duration of pedological drought. Frequently, this is examined only through the prism of atmospheric and hydrological drought, not taking into account the reduction of the water conservation capacity in the soil, the disruption of the water circuit in the soil profile as a result of the increase in humidity values that interrupt capillary continuity, the formation of physical barriers that limit the capillary rise of water from the inner to the upper horizons.

The formation of barriers is, indispensably, associated with the inhomogeneity of the physical state and is caused by the differentiation of the hydrological profile into 3 hydrological horizons: arable (Aph 1), structured agrogenic, structured subarable (Aph2) and the native transition horizon which is to a lesser extent directly influenced by the transformations induced by agrogenesis and to a greater extent by the transformations carried out in the agrogenic layer as a result of the impact induced by the heterogeneity of the physical state of the soils.

The hydrological profile of arable chernozems is differentiated into the agrogenic layer (Aph1+Aph2) and the native layer. This leads to the establishment of a specific water regime in arable chernozems, materialized in intensive water loss during physical evaporation and reduction of productive water reserves in the underlying horizon. As a result, the natural mechanisms of self-reproduction of the structural-functional organization of the physical soil system are disturbed. In this regard, in our research, the emphasis has been placed on studying the entire complex of properties: structural-aggregate composition, its hydrostability, density, total and differentiated, porosity, directly or indirectly responsible for water reserves in the soil, especially productive ones, the ability to conserve and rationally consume it during evapotranspiration, etc., not only in terms of the degree of providing plants with water and producing crops, but rather in terms of the meaning and intensity of typogenetic and associated processes. In this context, our research has shown that under conditions of genetic homogeneity of the soil cover, there is an increased variability in the humus content, structural-aggregate composition, apparent volume density and composition of the porous space.

In this context, we draw attention to the high degree of spatial variability of the total volume of soil porosity, but also of the pores occupied by water and those of aeration. In most cases, the volume of aeration pores exceeds the volume of pores occupied by water by about 1.5-2.0 times. In our opinion, in the case of arable chernozems, "aeration pores" rather present microcracks through which water is intensively evaporated from the soil.

Within the control variant (forest strip) "aeration pores" represent macropores formed by the roots of strongly developed grassy vegetation.

3. Redistribution of humidity and promotion of seasonal overwetting.

The spatial inhomogeneity of the physical state of arable chernozems plays a crucial role in the redistribution of water from precipitation to atmospheric precipitation both in space and in the soil profile.

The physical inhomogeneity of the soil profile implies a reduction in water permeability and hydraulic conductivity and, as a result, water stagnation in the agrogenic layer of the profile, manifested in its seasonal overwetting (Tab. 5).

Table 5.

Spatial variability of the porosity difference of chernozem soils under conditions of seasonal superficial overwetting

Profile No.	Depth, cm	Porosity, % (E)					
		ε_t	ε_w	$\varepsilon_{f.s.l.}$	$\varepsilon_{f.l.l.}$	ε_k	ε_{aer}
1	0-10	62,7	31,8	8,0	4,8	19,0	30,9
	10-20	62,3	33,8	8,1	4,8	20,9	28,5
	20-30	62,0	33,9	7,8	4,5	21,6	28,1
	30-40	61,9	33,5	7,7	4,6	21,2	28,4
	40-50	61,6	32,0	7,6	4,3	20,1	29,6
2	0-10	60,0	27,6	7,9	4,9	14,8	32,4
	10-20	58,2	32,6	8,2	5,1	19,3	25,6
	20-30	57,6	34,7	8,3	5,3	21,1	22,9
	30-40	53,8	34,0	8,6	5,6	19,6	19,8
	40-50	52,9	34,8	8,7	5,6	20,1	18,1
3	0-10	57,8	39,4	8,5	5,1	25,8	18,4
	10-20	55,2	40,3	9,3	5,8	25,2	14,9
	20-30	53,4	40,2	9,6	5,7	24,9	13,2
	30-40	52,9	38,8	9,6	5,7	23,5	14,1
	40-50	52,7	38,3	9,8	5,9	22,6	14,4
4	0-10	55,3	44,0	9,0	5,4	29,6	11,3
	10-20	55,8	45,0	9,0	5,4	30,6	10,8
	20-30	56,6	42,0	9,0	5,4	27,6	14,0
	30-40	52,1	45,2	10,0	6,0	29,2	6,9
	40-50	50,9	44,8	10,4	6,2	28,2	6,1

*1- Typical weakly humiferous chernozem; 2 - Wetted chernozem soil;

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*3- Wet chernozem soil; Wet chernozemoid soil.
** Ɛt – total porosity; Ɛw- porosity occupied by water; Ɛf.s.l. – porosity occupied by physically stable bound water; Ɛf.l.l.- porosity occupied by labile bound water; Ɛk – capillary water

Table 6.

Spatial variability of the structural-aggregate composition of chernozem soils under conditions of seasonal superficial overwetting

No.	Depth, cm	Aggregate diameter, mm. Aggregate content, %						Structuring coefficient Ks	Hydrostability coefficient Kh
		Dry fractionation							
		>10 mm	∑10-0,25 mm	∑>10+<0,25 mm	∑0,25-5 mm	>0,25 mm	<0,25 mm		
1*	0-10	6,7	87,6	12,4	65,3	61,4	38,6	7,06	700
	10-20	8,9	86,0	14,0	65,2	60,8	39,2	6,14	706
	20-30	7,3	88,8	11,2	64,4	58,8	41,2	7,92	662
	30-40	8,2	86,5	13,5	60,1	57,1	42,9	6,41	660
	40-50	9,0	83,8	16,2	55,3	50,4	49,6	5,17	601
2*	0-10	18,4	78,5	21,5	59,0	58,4	41,6	3,65	744
	10-20	15,5	80,2	19,8	58,3	57,8	42,2	4,05	724
	20-30	19,9	76,5	23,5	54,0	53,1	46,9	3,23	694
	30-40	17,2	79,2	20,8	56,1	52,3	47,7	3,81	660
	40-50	14,6	81,0	19,0	54,8	50,1	49,9	4,26	619
3*	0-10	21,6	75,4	24,6	51,5	52,3	47,7	3,07	693
	10-20	25,5	71,9	28,1	50,0	50,9	49,1	2,56	707
	20-30	24,8	72,2	27,8	51,3	50,7	49,3	2,60	702
	30-40	24,3	72,3	27,7	50,3	51,4	48,6	2,61	711
	40-50	23,9	73,2	26,8	49,1	50,9	49,1	2,73	695
4*	0-10	22,4	74,7	25,3	56,3	57,1	42,9	2,95	764
	10-20	23,8	73,7	26,4	57,8	60,3	39,7	2,79	818
	20-30	23,6	74,0	26,0	54,6	56,1	43,9	2,85	758
	30-40	24,0	73,2	26,8	52,3	56,8	43,2	2,73	776
	40-50	24,3	73,3	26,1	53,1	55,8	44,2	2,83	724

*Typical weakly humiferous chernozem; Moist chernozem soil; Wet chernozem soil; Wet chernozemoid soil; Wet chernozemoid soil

In the early phase (typical slightly humiferous moistened chernozem) overwetting practically does not involve changes in the structural-aggregate composition (Tab. 6) and is manifested only in higher moisture contents (Ɛw), including capillary water (Ɛt). Over time, however (3-4 years) significant changes in soil structure occur in soils, manifested in bouldering of the structure (more than 2-fold increase in the aggregate fraction >10 mm) associated with deep cracking of the agrogenic layer and preferential water drainage paths into the underlying layers.

As a result, seasonal overwetting is replaced by periodic overwetting (moistened chernozem soil) and subsequently permanent with permanent overwetting (wet chernozem and chernozemoid soils).

As the overwetting develops, the overwetted spaces transform into microdepressions in which, during the wet period, water from the leaks from the related spaces accumulates, intensifying the degree of overwetting, reducing the aeration porosity below critical limits (15%) and carrying out anaerobic processes uncharacteristic of chernozems. Within such spaces, the overwetting is supported by hydrophytic vegetation that develops rapidly.

CONCLUSIONS

The intensive use of soils, especially chernozems in the agricultural circuit leads to the systematic disturbance of the state of soil settlement which over time manifests itself in the initiation of processes of spatial non-homogenization of the physical state of the soil.

In the early stages this is more pronounced in spaces with natural inhomogeneity caused by geomorphological conditions and the particularities of the parental deposits. Over time, however, these intensify as a result of the unidirectional degradation of the soil structure and the associated dehumification and manifest themselves in the reduction of the self-reproduction capacity of the physical subsystem of the soil. This leads to the establishment in chernozems of two opposite trends of arid and neohydromorphic evolution of chernozems and increased vulnerability to climate change with the subsequent modification of the type of pedogenesis.

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