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COMPACTION OF ARABLE CHERNOZEMS: PEDOFUNCTIONAL AND AGROTECHNOLOGICAL CONSIDERATIONS

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Abstract

The contemporary evolution processes of arable chernozems lead to the modification of the indices of the agrogen layer settlement state materialized in the change of the ratio between the mass and the volume of the soil phases in the evolutionary-genetic sequence: compaction → overcompaction → settling → vertisolation. It is favored by the high proportion of interaggregate pores, humus loss, disaggregation and destructuring of soil, the increased content of fine clay (< 0.001 mm) in the physical clay (< 0.01 mm), the low degree of saturation of physical clay with humus, the high proportion of smectite-montmorillonites in the composition of clay minerals of the fine clay fraction. The modification of the settlement indices conducts to the establishment of some regimes and processes in soils with an impact on the direction and intensity of the evolution processes of chernozems in arable regime, with the involvement of new mechanisms and processes uncharacteristic for native chernozems: compaction and overcompaction of structural aggregates, eluviation of finely dispersed clay from the arable layer to the sub-arable layer, reduction of the intensity of the chernozemous process. These lead to the detachment of the arable chernozems from the native ones and implies the need to establish a new management paradigm of arable chernozems in the framework of bioremedial adaptive-landscape technologies.

Key words: *compaction, differential porosity, humus loss, vertisolation, settling.*

INTRODUCTION

The multiple pedological investigations carried out in the Pre-Danubian area since the nineties of the 19th century have shown, unanimously, that the structure of its soil cover is dominated by leached and typical chernozems with moderate and low humus content, a medium-fine granulometric composition (clayey loamy and loamy clayey) with an increased degree of potential fertility. The vertiginous development of intensive agriculture in the post-war period attracted their inclusion in the agricultural circuit, the degree of their utilization in agriculture reaching more than 86% at the end of the nineties of the last century. The substitution of natural biocenoses with agrophytocenoses led to the significant modification of all regimes (hydric, thermal, aeration, aerohydric, hydrothermal) and processes (formation and accumulation of humus; aggregation-structuring; biogenic accumulation) responsible for chernozemic pedogenesis, including the entire complex of pedo-biological processes, which determine the peculiarities of the biological circuit of substances and the functioning of the soil ecosystem (Jigau et al., 2021). In addition, a series of modification-transformation processes of all components and phases of chernozems were established in the soils.

According to the calculations, even in the first 5-10 years of the restructuring of the soil ecosystem included in the agricultural circuit, an unidirectional trend of mineralization of organic substances, including humus, was established in them. The losses of humus from these during the last 100 years made up more than 25% of the initial reserves (Ursu, 2011). The composition of the system of humic substances also suffered significant changes, manifested in its fulvatization.

Under the conditions of significant changes in the pedofunctional regimes (aerohydric, hydrothermal, redox) within the humification process, complex humic substances characteristic of the chernozemic process are no longer produced. As a result of the intensification of biogenic alteration processes in the arable layer of clay minerals from the group of hydromics, perceptible mineral changes are attested in it (Tshovrebov et al., 2017).

The specified changes attracted, by themselves, the establishment in the arable chernozems of a new mechanism of spatial organization of their organo-mineral component, which involves the disintegration-metaaggregation of the chernozemic structure with the development of agrogenic aggregate formations (Jigau et al., 2021).

The inter-determined and interdependent modification of the humification and aggregation-structuring processes led to the disruption of the functionality of the pedofunctional system [humic system ↔ aggregate system] manifested in the change in the state of soil settlement, the integrative indices of which are the bulk density (compaction) and the pore space of soils.

Despite the multiple researches dedicated to soil compaction in Soil Physics, until now no comprehensive concept has been formulated regarding the factors and processes that determine it. It is certain that soil compaction is a phenomenon inherent to the inclusion of soils in the arable circuit (Jigau and Nagacevschi, 2006).

In this sense, in the scientific literature soil compaction is examined through the lens of its perception as a result of the change in the way of organizing their solid component under the action of intensive works and the exaggerated traffic of machines and agricultural aggregates on the land surface.

In this paper, soil compaction is examined through the lens of disrupting the functionality of the pedofunctional system [bioenergetics system ↔ aggregate system].

MATERIALS AND METHODS

In this paper, soil compaction is examined as a phenomenon of change in the ratio between mass and volume of soil phases through the prism of the energetic concept of physical state (Voronin, 1990) and the thermodynamic concept of soil quality (Смачин, 2021). In accordance with these and through the prism of the concept of hierarchy, interdependence and interaction of soil properties, regimes and pedogenetic processes (properties ↔ regimes ↔ pedogenetic processes) within anthropo-natural pedogenesis, compaction is a complex polygenetic process inherent in its evolution and represents an early phase within of the evolutionary-genetic chain “compaction → overcompaction → settling → vertisolation” of changing the ratio between the mass and the volume of the soil phases manifested in various ways of structural-functional organization of the soil mass.

The realization of the mentioned evolutionary-genetic chain is favored by the increased compaction-slitic potential determined by the medium-fine granulometric composition (clayey loamy and loamy clayey), the increased content of fine clay (< 0.001 mm), the increased degree of unsaturation of the physical clay (< 0.01 mm) with humus, illite-montmorillonite composition of fine clay.

The driving force of compaction and its evolution is a series of agrogenic processes (humus loss, hydrophilization of the organo-mineral matrix, disaggregation-destructuring of the soil mass, mineral transformations in the mineralogical composition of the fine clay fraction as a result of the intensification of biological alteration processes in the arable layer), the changes in pedogenetic and pedofunctional regimes induced by climatic instability, the mechanical pressures exerted on the soil by machines and agricultural aggregates.

In accordance with the work concept presented above, the activities in the laboratory included:

1. Determination of the dynamics of the bulk density in a multi-year regime - the N. Kacinski compactimeter method (Jigau, 2006).
2. Determination of the density and porosity of aggregates 5-1 mm - the Lâtaev method (Jigau and Nagacevschi, 2006).
3. Determination of the dynamics of the structural-aggregate composition - the Savvinov method (Jigau and Nagacevschi, 2006).
4. Determination of the mineralogical composition of the fine clay fraction (< 0.001 mm) - diffractometric method.
5. Calculation of differential porosity - suction curve method.

RESULTS AND DISCUSSIONS

With reference to agricultural soils, two categories of compaction are more frequently examined in the scientific literature: a) primary, b) secondary (agrogenic). Primary compaction is examined as a trait inherited from the parent rock with some modifications induced by the pedogenesis process. Agrogenic compaction, more often, is examined simplistically through the lens of the utilitarian approach in relations with agricultural aggregates and cultivated crops. In this sense, soil compaction is defined as a process caused by excessive and irrational traffic on the land for agricultural works, especially in inadequate moisture conditions, as a result of which the apparent density values increase above the optimal values for agricultural crops, but remain in the range of values within which decompaction is ensured by self-loosening. Unlike the primary compaction in the soil profile, this is limited only to the agrogenic layer within which two layers with different compaction mechanisms are clearly outlined: a) arable and b) sub-arable.

The compaction of the arable layer is a very common phenomenon, which occurs during intensive tillage of the soil and is determined by its degradation-metastructuring: tillage → substitution of biocenoses with agrophytocenoses → destruction of the soil layer → degradation of humic detritus → degradation of the humic system → destructuring-metaaggregation-compaction.

The realization of this mechanism does not involve the formation of new swelling or agglutinating mineral formations and is determined by the modification of the way the solid constituents are placed. The effects of compaction are intensified by the pressure exerted by the mass of agricultural machines.

The phenomenon of compaction of the sub-arable layer is usually known as "plow sole", although its origin is not only caused by plowing works. The sub-arable layer, unlike the arable layer, is more easily compacted because it is wetter and is characterized by a more rigid settlement under the action of the pressure exerted by the mass of the overlying layer, the lower content of organic matter, less structured and the structure is less stable. In it, the compaction is intensified by the metaaggregation processes under the influence of the mechanical forces exerted by the agricultural aggregates. As a result, the total volume of the porous space is significantly reduced in the sub-arable layer due to the interaggregate pores with the formation of prismoid-nut-shaped aggregate formations.

The clearly described mechanisms are outlined in the agrophysical profile of arable chernozems (Table 1).

Table 1. Dynamics over time and on the profile of the bulk density of the typical loamy chernozem with low humus content on clay loam in the period 2010-2019 (LLC VINDEX-AGRO, Orhei district)

Horizon	Depth, cm	2010		2013		2016		2019	
		1*	2**	1*	2**	1*	2**	1*	2**
Am/Aar	0-10	1.02	1.26	1.00	1.23	0.98	1.21	1.01	1.25
	10-20	1.05	1.24	1.03	1.25	1.02	1.26	1.03	1.20
	20-30	1.14	1.24	1.14	1.28	1.13	1.24	1.11	1.24
Am Bm	30-40	1.18	1.33	1.20	1.35	1.12	1.34	1.17	1.33
	40-50	1.22	1.36	1.25	1.35	1.22	1.37	1.22	1.35
Bma	50-60	1.28	1.34	1.27	1.35	1.27	1.35	1.25	1.34
	60-70	1.30	1.35	1.32	1.34	1.30	1.34	1.33	1.34
	70-80	1.29	1.33	1.33	1.33	1.32	1.35	1.31	1.36
B2ca	80-90	1.32	1.33	1.33	1.35	1.31	1.34	1.30	1.34
BCca	90-100	1.33	1.32	1.32	1.34	1.30	1.32	1.31	1.32
Cca	110-120	1.30	1.30	1.31	1.33	1.31	1.33	1.32	1.33

1* - nativ
2** - arable

From Table 1 we can see that the chernozems systematically subjected to the works are detached from the unworked chernozioms by higher values of the bulk density in the arable layer (0-30 cm). Compared to the native chernozems in the arable layer of the arable chernozems, the bulk density values are by 0.1-0.2 g/cm^3 higher and indicate the establishment of the compaction process in them. At the same time, during the observation period, the bulk density values in it remain in the range of optimal values within which the return to the balanced values is ensured through self-loosening and self-decompaction.

In the native chernozems, the bulk density values in the 30-60 cm layer increase slightly but remain in the range of optimal values (< 1.30 g/cm). The slight but noticeable increase in the values of the bulk density in this layer of the native chernozems is caused by the reduction of the role of the root mechanism in the self-loosening of the soil. In the same layer of arable chernozems, during the entire period of observations, the bulk density shows values characteristic of the range of critical values for chernozems (1.3-1.4 g/cm^3), which indicate the overcompaction process. In it, the self-decompaction processes ensure only the partial decompaction of the soil mass, in connection with which the bulk density values are established at a higher, but relatively stable, level. This implies the conclusion that the overcompaction of the 30-60 cm layer is only partially caused by the mechanical forces originating from the traffic on the soil surface and its work and is achieved due to the reduction of the interaggregate pore volume. At the same time, in the sub-arable layer, a reduction in the volume of the aggregate pores can be observed as a result of their clogging with finely dispersed particles leached from the arable layer (Tables 2, 3).

Table 2. The density and porosity of the 5-1 mm aggregates of typical weakly and moderately humic arable chernozems under conditions of various tillage systems (agrogenic layer 0-50 cm)

Soil, Crop	Aggre-gate diameter, mm	Depth, cm, density (g/cm3) and porosity (%) of aggregates															
		Conventional technology								Adaptive-landscape technology							
		0-15		15-20		25-30		45-30		0-15		15-20		25-30		45-30	
		1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Typical chernozem with low humus content, winter wheat	5-3	1.59	38	1.63	37	1.69	35	1.64	36	1.54	38	1.57	39	1.63	37	1.60	39
	3-2	1.61	37	1.68	35	1.75	32	1.72	34	1.57	38	1.63	37	1.70	34	1.66	36
	2-1	1.64	36	1.73	33	1.86	28	1.80	31	1.60	37	1.69	34	1.79	31	1.74	33
Typical chernozem with low humus content, winter barley	5-3	1.57	38	1.60	38	1.70	34	1.67	36	1.53	40	1.57	39	1.61	38	1.57	40
	3-2	1.62	36	1.70	34	1.88	27	1.79	31	1.58	38	1.62	37	1.73	33	1.69	35
	2-1	1.66	35	1.83	29	1.94	25	1.87	28	1.65	35	1.70	34	1.80	31	1.73	34
Typical chernozem with medium humus content, rape	5-3	1.58	38	1.63	37	1.71	34	1.68	36	1.53	40	1.60	38	1.68	38	1.60	39
	3-2	1.65	35	1.76	32	1.85	29	1.81	31	1.57	38	1.63	37	1.71	34	1.58	39
	2-1	1.72	33	1.88	27	1.97	24	1.92	26	1.67	36	1.74	34	1.77	32	1.71	34

Table 3. Differential porosity of typical chernozems with moderate humus content and different degrees of agrogenic transformation (0-50 cm agrogenic layer)

Soil	Depth, cm	Porosity, %					
		Total	Occupied with water	Occupied by physically stably bound water	Occupied by physically weakly bound water	Occupied by capillary water	Aeration
Typical chernozem with moderate humus content (Dendrarium 63 years)	0-10	63.8	31.9	8.1	4.6	19.1	31.9
	10-20	62.9	33.2	8.0	4.8	20.4	29.7
	20-30	62.5	33.6	7.8	4.7	21.3	28.5
	30-40	62.0	31.5	7.8	4.7	19.0	30.5
	40-50	31.8	30.8	7.8	4.9	17.7	31.4
Typical chernozem with moderate humus content (fallow ground 26 years)	0-10	65.2	33.2	7.3	4.4	21.5	32.0
	10-20	61.5	32.7	8.2	5.1	19.4	28.8
	20-30	59.7	32.5	8.4	5.2	18.9	27.2
	30-40	57.0	31.9	8.6	5.0	18.3	25.1
	40-50	53.2	29.0	8.6	5.0	15.4	24.2
Typical chernozem with moderate humus content arable	0-10	57.8	29.4	7.7	4.7	17.0	28.4
	10-20	56.1	29.2	8.1	5.0	16.1	26.9
	20-30	54.6	28.8	8.4	5.0	15.3	25.8
	30-40	53.4	28.5	8.4	5.3	14.8	24.9
	40-50	52.7	27.7	8.4	5.6	13.7	25.0

From Table 2, we can see that the aggregates in the sub-arable layer are characterized by the compaction of the aggregates and the reduction of the aggregate porosity. This allows us to conclude that the evolution of the compactness regime of the sub-arable layer of the arable chernozems is caused by a new process - luvic, that is not characteristic for the native chernozems, manifested in migration of the organo-mineral clay from the arable layer. This process is favoured by the more advanced level of leaching of the arable layer of the arable chernozems, the reduction of the calcium content retained in the adsorptive complex, the narrowing of the Ca: Mg ratio, the reduction of the humus content and the increase of its degree of mobility, the reduction of the degree of bond stability coagulation within organo-mineral compounds, increasing the degree of hydrophilicity of mineral colloids (Medvedev, 2014). All these contribute to the mobilization of the finely-dispersed fraction, its reorientation and periodic downward migration from the Aar/A horizon to Am-Bm and cause the unidirectional clogging of the aggregate pores.

The reduction of the aggregate pore volume causes the accumulation inside the aggregates of the products of incomplete decomposition of organic matter, the reduction of microbiological activity, the realization of reduction reactions in some isolated spaces uncharacteristic of the derno-chernozemic pedogenesis. More frequently, they are carried out in the spring or during periods of heavy rainfall when the humidity level corresponds to the values of the field capacity for water.

V. V. Medvedev admits that these reactions can also take place in other periods but in the spaces inside the aggregates. In the conditions when the porosity of the aggregates presents values below 40%, the mineralization processes of the organic matter and the transformational activity are significantly reduced. According to the quoted author, the derno-chernozemic process is located on the surface of the aggregates where they contact the interaggregate pores (Medvedev, 2016). The cited author believes that the derno-chernozemic process is no longer characteristic of all aggregates. In some of these, another process of decomposition-transformation of organic matter is probably carried out. It is certain that this is not done in the aggregates in the arable layer that is periodically subjected to work. On the other hand, in the 30-60 cm (overcompacted) layer, a series of features involved by them can be seen. Thus, the 30-60 cm layer turns out to be a metamorphosed formation (modified *in situ*) - a new genetic horizon as a result of the accumulation in it of the multi-year effects induced by overcompaction.

The reduced flow of water inside the aggregates, the increased aggregate density, the establishment of unfavorable conditions for the realization of the process of humus formation, all these indicate the reduction of the intensity of the chernozemic pedogenetic process (Table 4).

Table 4. Pedofunctional-genetic effects caused by the degradation of the settlement indices of arable chernozems in the Pridanubian area

Criteria	The content and direction of pedofunctional processes	Pedofunctional-genetic effects
Humification-mineralization.	The accumulation of partially decomposed and pseudohumic organic substances in the aggregate pores.	Reducing the intensity of typogenetic processes (formation and accumulation of humus; aggregation-structuring).
Biological and microbiological activity.	Reduction and degradation of biodiversity and biological activity of soils.	Partial (mosaic) abiotization of the subaerial layer.
Change of relations: solid phase-solid phase	Increasing the volume of physically (thermodynamically) bound water.	Conservation of substances in aggregates, reduction of their migration capacity in the soil profile.
The formation of liquid and solid surface leaks.	Spatial differentiation of substances within the landscape.	Intensification of erosion.
Pollution and overwetting of pressure elements of the landscape.	Migration of pollutants.	Accumulation of pollutants and reduction of biological processes.
Changing the water balance in the soil and the water regime.	Neohydromorphization of the soil.	Hydrometamorphism. Hydrological degradation.

The mentioned points to early features of a new type of migration and transformation of finely dispersed fractions in the overcompacted layer of arable chernozems.

In the underlying horizons, the difference between the bulk density values in native and arable chernozems is reduced to a minimum. This implies the conclusion that in native conditions the bulk density is a quasi-balanced parameter corresponding to bioclimatic conditions and in agrogenesis conditions it is an unbalanced parameter (Medvedev, 2016).

The phenomenon of overcompaction of arable chernozems has a residual-cumulative character which is caused by the reduction of the decompaction capacity as the degree of structure degradation increases as a result of the condensation of the structural elements. As the degree of degradation of the structure increases, the balanced values of the bulk density are established at a higher level (Сорочкин, 1989). In this context, an important factor favouring the overcompaction of arable chernozems is the humus loss that causes the reduction of aggregate stability.

Starting from this, we consider that the bulk density and the structural-aggregate state are interdetermined and interdependent. The structure of the soil is achieved by the dynamics of the degree of compactness and the last by the structural-aggregate state. The integrative index of these interactions is the volume, structure and dynamics of the porous space. Through this prism of ideas, the basic function of the soil structure is to ensure an optimal degree of compactness of the soil and an optimal settlement state for achieving eco- and agro-ecosystem functions. The way of structural-functional organization of the soil mass determines the structural-aggregate state expressed in the dimensions, properties of aggregates (aggregate density, aggregate porosity, aggregate stability) and the ratio between aggregates with various pedofunctional functions (Jigau, 2009). These, in turn, are a function of the composition and properties of the structural elements at the microaggregate level and their interaction characterized by the type of structural links.

From the perspective of the basic function of the aggregate structure of soils, the basic criterion for evaluating the quality of the structure is the dynamics of the degree of compactness of the soil (Сорочкин, 1989). Optimal quality of the structure is considered in the absence of seasonal pulsations of the structural-aggregate composition and the bulk density of the soil. This is considered satisfactory in the case of attenuated pulsations of the structural composition and bulk density. Unsatisfactory quality is characterized by a very high degree of seasonal variability of structural composition and bulk density.

Table 5. Dynamics of the structural-aggregate indices of the arable chernozems in the space between the Prut and Dniester during the vegetation period

Soil	Depth, cm	Sample collection period											
		At the beginning of the vegetation period						At the end of the growing season					
		The dimensions of the aggregates, mm. Content of aggregates, %											
		>10	5-10	5-1	10-0.25	<0.25	Ks	>10	5-10	5-1	10-0.25	<0.25	Ks
Argilic chernozem	0-25	15.10	33.42	44.73	82.76	2.14	4.80	22.79	7.97	39.25	66.80	10.47	2.00
	25-40	17.12	36.19	41.34	81.12	1.76	4.30	26.33	47.17	24.99	72.97	0.70	2.70
	40-60	9.70	27.27	52.84	88.83	1.67	7.91	22.35	40.29	33.53	76.54	1.13	3.26
Argilic chernozem	0-25	-	24.38	63.80	97.36	2.64	36.50	43.16	29.03	26.87	55.02	1.82	1.44
	25-40	12.40	35.00	48.90	86.19	1.41	4.53	38.91	35.75	23.95	60.48	0.61	1.53
	40-60	6.42	26.75	62.34	92.26	1.32	11.92	10.51	19.19	61.65	87.30	2.19	6.87
Leached chernozem	0-25	11.35	39.33	41.96	86.68	1.97	6.50	24.43	33.17	34.45	73.05	2.52	2.71
	25-40	30.82	25.38	37.49	67.39	1.79	2.07	18.66	38.16	31.56	80.57	0.77	4.14
	40-60	6.24	30.40	52.42	90.60	3.16	9.63	47.03	18.38	14.69	52.31	0.66	1.10
Typical chernozem with moderate humus content	0-25	24.70	33.17	35.51	74.15	1.15	2.87	32.37	17.00	31.52	59.60	8.03	1.48
	25-40	39.68	24.28	33.24	59.94	0.38	1.50	20.70	36.93	37.70	77.63	1.67	3.47
	40-60	20.04	22.02	45.57	78.06	1.90	3.56	22.93	25.19	42.40	73.26	3.81	2.74
Typical chernozem with moderate humus content	0-25	8.36	26.29	56.26	90.02	1.62	7.82	7.84	25.96	51.95	87.30	4.86	6.87
	25-40	25.00	32.87	38.91	74.02	0.63	2.89	71.01	14.12	12.73	28.73	0.73	0.40
	40-60	20.48	20.34	50.33	77.95	3.28	3.28	38.12	19.31	32.31	58.31	3.57	1.40
Typical chernozem with low humus content	0-25	18.82	19.39	37.09	74.66	6.52	2.95	7.40	21.18	47.23	84.02	8.52	5.26
	25-40	16.33	43.09	47.46	82.94	0.73	4.86	10.36	40.76	36.78	88.78	0.86	7.91
	40-60	15.15	40.33	50.15	84.56	2.29	5.48	1.30	23.52	55.99	85.17	1.53	5.74
Typical chernozem with low humus content	0-25	-	13.43	59.18	91.01	8.99	10.13	10.31	18.20	47.54	81.60	8.08	4.44
	25-40	10.36	40.61	43.26	87.14	1.50	6.78	12.67	30.87	50.55	85.55	1.78	5.92
	40-60	5.45	38.67	50.59	93.87	0.68	15.16	15.40	20.55	59.63	83.42	1.18	5.03

Table 6. The dynamics of the settlement indices of the arable chernozems in the area between the Prut and the Dniester

Soil	Depth, cm	Sample collection period			
		At the beginning of the vegetation period		At the end of the growing season	
		Indices of the state of settlement			
		Bulk density, g/cm^3	Total porosity, %	Bulk density, g/cm^3	Total porosity, %
Argilic chernozem	0-25	1.12	60.0	1.34	47.0
	25-40	1.28	50.2	1.37	46.7
	40-60	1.24	52.0	1.33	48.8
Argilic chernozem	0-25	1.08	57.5	1.30	48.8
	25-40	1.23	52.1	1.39	45.9
	40-60	1.20	53.8	1.36	47.7
Leached chernozem	0-25	1.03	59.4	1.32	48.0
	25-40	1.20	53.3	1.34	47.9
	40-60	1.16	55.4	1.30	50.0
Typical chernozem with moderate humus content	0-25	1.06	58.3	1.33	47.6
	25-40	1.24	51.8	1.39	45.9
	40-60	1.18	54.6	1.37	47.3
Typical chernozem with moderate humus content	0-25	1.10	56.6	1.34	47.2
	25-40	1.26	51.0	1.41	45.1
	40-60	1.20	53.8	1.37	47.3
Typical chernozem with low humus content	0-25	1.06	58.3	1.35	46.7
	25-40	1.28	50.2	1.46	43.2
	40-60	1.23	52.3	1.40	46.2
Typical chernozem with low humus content	0-25	1.02	59.8	1.29	49.2
	25-40	1.19	53.7	1.43	44.4
	40-60	1.17	55.0	1.37	47.3

Our research has highlighted an increased degree of instability during the vegetation period of the indices of structural-aggregate condition and bulk density (Tables 5, 6).

This allows us to conclude that in the Pridanubian area predominate arable chernozems with satisfactory quality of the aggregate structure, which implies the establishment, over time, of the phenomenon of settling and vertisolation.

Unlike compaction and overcompaction, settling of arable chernozems involves not only reducing the total volume of interaggregate pores but also reducing the volume and diameter of capillary aggregate pores and transferring them to the category of textures occupied by physically bound water.

This leads to the reduction of the swelling capacity of the aggregates and that of self-restoration and attributes to the compacted layer an unidirectional trend of exaggerated increase of soil mass per volume unit and the development of the vertisolation process.

According to И. В. Ковда the phenomenon of vertisolation involves 3 main notions: vertisolation potential, vertisolation, genesis of vertisolation (Ковда, 1995).

The vertisolation potential defines the degree of predisposition of the soil to vertisolation manifested in high values of hardness, volumetric mass, swelling, contraction.

The vertisolation potential depends on the chemical, mineralogical, granulometric composition, the content of organic matter, the waterstability of the structure. Some of the listed factors are inherited from the parent rock but transformed during the pedogenesis process. Another part (humus content, waterstability of the aggregate structure) is determined directly by the pedogenesis process (Сорокин, 2016). In this sense, we believe that it is more appropriate to distinguish between passive vertisolation potential (factors inherited from the parent rock) and active vertisolation potential (factors from pedogenesis).

Through this prism of ideas, the arable chernozems in the Pridanubian area have a high passive vertisolation potential determined by the increased content of fine clay and the predominance of minerals partially (illite-hydromic) and strongly (smectite-montmorillonite) swelling in the mineralogical composition of the fine clay (Table 7).

Table 7. Mineralogical composition of the fine clay fraction (‹0.001 mm) of weakly and moderately humiferous typical chernozems (Data provided by T. V. Popov)

Soil	Genetic horizon	Depth, mm	Fine clay content, %	Mineral content % of clay mass		
				Smectite montmorillonite	Hydromics	Kaolinite Chlorite
Typical clayey loamy arable chernozem with low humus content (Orhei district)	Aar 1	0-20	29	37	52	11
	Aar 2	20-35	31	43	48	9
	Am Bca	40-60	30	49	37	14
	Bca	60-75	28	49	39	12
Typical loamy arable chernozem with low humus content (Orhei district)	Aar 1	0-20	26	31	57	12
	Aar 2	20-35	24	35	55	10
	Am	35-45	24	35	54	11
	Am Bca	50-60	23	31	56	13
	Bca	70-85	21	30	60	10
Typical irrigated arable chernozem with moderate humus content (Orhei district)	Aar 1	0-20	29	51	44	5
	Aar 2	25-35	32	36	54	10
	Am	35-45	32	41	52	7
	Am Bm	50-65	31	39	49	12
	Bca	70-85	29	33	54	13

Realization of the vertisolation potential of chernozems, along with the listed factors, requires contrasting hydrothermal regime conditions. In this sense, the intensity of the vertisolation process is determined by the amount of atmospheric precipitation, temperature, and the dynamics of their change.

The wetting-drying regime, in the context of realizing the vertisolation potential, also depends on the relief conditions, the degree of natural drainage, the density of the vegetation cover, the presence and level of phreatic and pedophreatic waters.

Through this prism of ideas, the realization of the vertisolation potential of the chernozems in the Pridanubian space is favored by the alternation of states of excessive wetting, during periods with abundant precipitation, and those of rapid overdrying caused by high temperatures. The longer the period between precipitations, the greater the degree of vertisolation (Jigau, 2009; Fala and Jigau, 2018).

The decisive role in limiting the realization of the vertisolation potential of the chernozems in the region belongs to the process of formation and accumulation of humus and that of aggregation-structuring. In this sense, it was established that the more intensively they occur, the lower the degree of realization of the vertisolation potential. As a result, within the native chernozemic pedogenesis, the soil vertisolation process is only evidenced in the spaces where it takes place with the participation of phreatic waters, so that in the pedological investigations carried out in the 50s of the 20th century, the vertisolation of chernozems is evidenced in restricted spaces. This has increased in arable chernozems more recently as a result of the humus and soil structure loss under conditions of natural-anthropic chernozem pedogenesis (Jigau and Lesanu, 2012).

In the opinion of the cited authors, in the arable chernozems of the Pridanubian area, vertisolation is favored by the changes in the pedofunctional regimes and elementary pedogenetic processes induced by the intercalated action of agrogenesis and climate changes. At the same time V.S. Tshovrebov et al. believes that increasing of vertisolation potential and its realization in arable chernozems are favored by the processes of biological alteration of hydromics in the arable layer with the formation of smectite-montmorillonite and mobile colloidal compounds of silicium (Tshovrebov, 2017). According to the cited authors, the content of mobile colloidal silicon compounds in the arable layer of the chernozems exceeds their content in the A horizon of the native chernozems by 2-3 times, given that the hydromic alteration process does not take place in them because they have a balanced balance of potassium. In this context, they consider that the vertisolation of chernozems implies seasonally variable changes coming from the consolidation-deconsolidation of the soil mass, and its trend is determined by the direction and intensity of the transformation processes of the mineral component and has an unidirectional character.

Through the thermodynamic concept of the physical state of soils A.V. Smaghin believes that vertisolation is caused by the reduction (about 2 times) of the effective thickness of the water layer which is thermodynamically bound of the dispersed system with the intensification of the interactions between elementary soil particles (compaction effect) (Смагин, 2020).

According to the cited author, the vertisolation process is based on the physical-mechanical mechanisms of interaction of finely dispersed particles and water molecules within the swelling-contraction cycles.

In this context, vertisolation is a process of destruction of the initial structure of the soils that leads to the formation of vertic horizons with a massive blocky structure with a plastic consistency in the wet state and consolidated in the dry state. Through this prism of ideas, vertisolation is a secondary degradative process of a natural-anthropic nature that leads to the formation of metastructured arable and subarable horizons. Vertisolation is manifested in the consolidation of the soil mass from the agrogenic layer in blocks with a diameter > 50 cm, separated by deep cracks with a width > 3-5 cm. Thus, vertisolation represents the primary phase of the vertisolation process, which involves the evolution of the anthropo-natural chernozemic pedogenesis with the formation of secondary slitozems.

According to I.V. Kovda et al. genesis of vertisolation should be examined along with other types of pedogenesis: chernozemic, podzolic, halomorphic, etc. (Kovda, 1992).

In contrast to these, genesis of vertisolation is distinguished by cyclical self-development, which is manifested in the intensification or attenuation of the degree of complexity of the soil cover of agrolandscapes determined by the degree of interdetermined and interdependent physical degradation caused by the disruption of the functioning of the pedofunctional system [bioenergetic system ↔ aggregate system].

According to several authors, genesis of vertisolation includes a series of elementary processes corresponding to bioclimatic conditions. In the case of arable chernozems, genesis of vertisolation involves the processes of formation and accumulation of humus, transformation of clay minerals, argillization, metaaggregation-metastructuring (Jigau, 2021; Jigau et al. 2022).

In this context, depending on the concrete bioclimatic conditions, genesis of vertisolation assumes several distinct forms.

According to V.R. Volubuev and F.I. Kozlovski vertisolation of arable chernozems is caused by the increase in colloidal activity as a result of the partial decalcification of the agrogenic layer (Володуев, 1948; Козловский, 1987), the increase of magnesia content in the adsorptive soil complex as a result of the decalcification of the agrogenic layer, the increase of the dispersion factor of the agrogenic layer caused by the humus loss with the intensification of the degree of hydrophilicity of the fine clay (Jigau, 2021).

An important factor favoring the genesis of vertisolation of arable chernozems are the changes induced by agrogenesis in the composition and properties of the basic soil material.

Loss of biota and humus led to the significant unsaturation of the physical clay fraction (< 0.01 mm) with humus and the increase in the degree of colloidal activity.

At the same time, the unidirectional expropriation of potassium (K_2O) with crops from the agrogenic layer intensified the transformation processes of hydromics into smectite-montmorillonite.

According to some authors, in these conditions, under the action of the pressures from the swelling of the soil mass upon wetting, the coagulation bonds characteristic of the chernozemic structure are replaced by condensation bonds with subsequent irreversible consolidation and the increase in their degree of stability during the drying shrinkage process (Корнблюм, 1972).

In accordance with the above, the vertisolation of arable chernozems involves three genetic-evolutionary stages: a) transformational - which involves all the processes, interacted and interdetermined, of quantitative and qualitative changes in the basic soil material and the structural-functional organization at all hierarchical levels of structural-functional organization of the soil; b) consolidation - all the processes of replacing the coagulation bonds between the solid components with condensation bonds that lead directly to the formation of the vertisolation state; c) the development and stabilization of the properties that determine the special vertisolation state due to the newly formed bonds as a result of the compaction and modification of the superficial properties (surface energy) (Корнблюм, 1977).

The bioclimatic and pedofunctional framework of the region creates conditions for the realization of the vertisolation process as a result of the modification of the structural links in the aggregate formations under the action of the pressures originating from swelling during wetting and contraction during drying.

The seasonal superficial overwetting, which has increased in the last 40-50 years, in the chernozemic areas, involved a new mechanism of vertisolation of the arable chernozems, which involves 2 phases: a) prevertisolation, which involves multiple processes of transformation of the basic matter of the soils in conditions of overwetting (quasi-gleyization, gleyization, montmorillonitization, argillization, solonetzization, etc.) materialized in increasing its vertisolation potential; b) vertisolation - the structural-functional organization of the soils in the newly created conditions with the formation of massive compacted blocks which leads to the extension of the vertisolation process upwards in the soil profile as a result of the residual-cumulative overwetting of the lower segment of the profile.

The vertisolation process in the lower layers of the profile is favoured by the mechanical barrier effects induced by the vertic layer on the soil surface.

In such conditions, through the preferential descended paths of water migration in the soil profile, water penetrates into the lower layers, and in dry periods the vertic layer on the surface creates impediments for capillary ascent and its physical evaporation from the soil surface.

The unidirectional vertisolation of the middle and lower segment is also favored by the lower waterstability of the aggregate structure as a result of the reduced content of humus and the greater weight of the aggregates formed with the participation of calcium carbonate. At the same time, in conditions of excessive humidity in the middle and lower layers of the profile, the activity of the mesofauna in the soil is significantly reduced (Fala, 2018). Depending on the evolutionary phase of the genetic-evolutionary chain, the degree of yield reduction, as a result of the change in the state of settlement, ranges from 5-25% depending on the crop in conditions of compaction-overcompaction, and up to 50-60% in conditions of settling/vertisolation (Fala and Jigau, 2018).

According to the same research the agro-technical processes practiced in order to optimize the agrogenic layer settlement indices, including deep loosening, only ensure its partial decompaction for a short period of time. Depending on the initial condition of the soils, the unfavorable settlement condition is restored in 1-2 years. At the same time, agrotechnical processes do not contribute to the decompaction and renewal of compacted structural aggregates. As a result, the effects caused by compaction persist even when the bulk density values fall within the range of optimal values. More than that, the residual compaction effects of the aggregates are maintained even under conditions of sustainable land management technologies (No-till, Mini-till). This implies the need to change the management paradigm of the agrogenic layer settlement indices in the framework of some bioremedial technologies based on the intensification of the biological processes of structural decompaction and stabilization of aggregates (Fala, 2018; Jigau, 2021). Summarizing the mentioned, we consider that the vertisolation of arable chernozems is a component part of the desertification process of chernozems (Figure 1).

CONCLUSIONS

The evolution of arable chernozems within the evolutionary-genetic chain “compaction – overcompaction - settling - genesis of vertisolation” assumes two hierarchical levels: a) the more rigid placement of the solid components materialized in the change in the ratio between the mass and the volume of the soil phases manifested in the total volume of the pores, its dynamics as well as the composition of the porous space: b) modification of the mechanisms and links of the formation of aggregates with the modification of their types materialized in the increase of aggregate density and the significant reduction of aggregate porosity.

This leads to the radical one-way modification of the pedological (hydric, thermal, aeration) and pedofunctional (aerohydric, hydrothermal, redox) regimes with the involvement of aridization → desertification elements of the soil cover. Within the current climate trend in the region, the specified phenomenon is intensifying and increasing, being favored by the interdependent and interdetermined degradation of the pedofunctional system [humic system ↔ aggregate system].

Combating the specified degradative processes implies the need for a new management paradigm of the physical state of soils based on the sustainability of the functionality of the pedofunctional system [humic system ↔ aggregate system] within adaptive-landscape-bioremedial technologies.

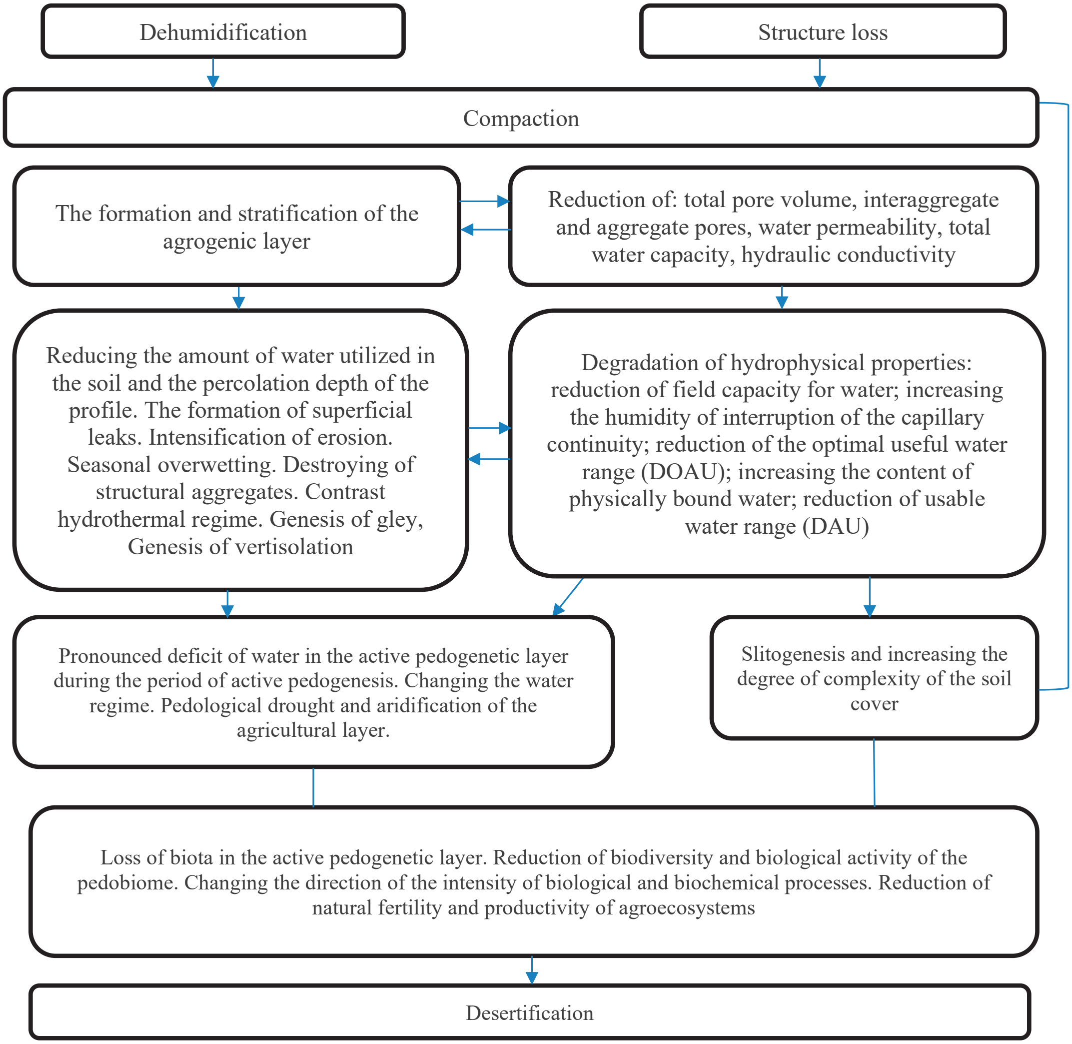

Figure 1. Hierarchy of desertification processes of steppe agro-landscapes under conditions of agrogenic modification of the state of settlement of arable chernozems

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