

Thermodynamic system of soil, its homeostasis, and probable mechanism of structure formation

S. Kolomiets

*Institute of Water Problems and Land Reclamation NAAS
37, Vasylykivska Str., Kyiv, 03022, Ukraine
e-mail: kss2006@ukr.net*

Goal. To substantiate the dynamic functional model of the thermodynamic system of the soil in interaction with cyclic environmental factors, to disclose internal homeostatic processes, the result of which is the reproduction of the soil structure. **Methods.** System analysis, theoretical — to generalize the specifics of soil structure and create its physical model; experimental — for laboratory research. **Results.** Laboratory hydrophysical tests of soil samples of the intact structure revealed the occurrence of hysteresis of water holding capacity of the soil, the value of which can reach 10 – 20%. The main reason for this phenomenon is the compression of air by liquid membranes in the pore space. The results of the influence of heating the soil sample of constant moisture saturation are presented, which fix the self-oscillating character of the dynamics of capillary potential in the soil. That testifies to the intra-porous redistribution of moisture and the local transport mechanism of convective transport of the matter. **Conclusions.** The interaction of soil with thermodynamic environmental factors transforms it into a micro gradient dissipative structure with the emergence of many subordinate processes. The main results of their action are the periodic increase of local thermodynamic availability of nutrition for plants and the formation of non-uniform in space cementation of dispersed particles, which become the nuclei of structural units. The concept of soil homeostasis, combining subordination processes, characterizes the level of energy consumption of the external energy flow, due to which the basic properties and structural organization of the soil are reproduced.

Key words: pore space, heterogeneity, hysteresis, thermodynamic system, synergetics, capillary potential, homeostatic processes.

DOI: <https://doi.org/10.31073/agrovisnyk202103-02>

Soil is a dynamic, living biosystem that is able to reproduce its properties under the action of natural and anthropogenic disturbances. Internal processes, due to which the basic properties and structural organization of the soil system are reproduced, and called homeostasis [1]. Identification of these internal (subordinate) processes in the soil will facilitate the transition to deterministic parametric models of soil interaction with environmental factors, which opens the way to conscious purposeful management of soil properties.

Insufficient attention has been paid to the study of soil interaction with the external environment related to soil ecology. Ideas of soil ecology, which were initiated simultaneously with the formation of genetic soil science by V.V. Dokuchaev, P.S. Kosovich, L.I. Prasolov, B.B. Polinov, V.G. Kornev, scientist school by V.R. Williams, and later developed by G.V. Dobrovolskyi, E.D. Nikitin, V.R. Volobuev, P.P. Nadochii, and other researchers, unfortunately, have not found practical application [2 – 4]. At this stage of the nascent of the ecology of soil was formed on the relationship between soil and environment, on the simultaneous action of soil formation factors, the concept of paragenesis of soils genetic types in accordance with the spatial variability of their conditions, the ecological functions of soils are determined. However, the interaction of soil with environmental factors in real-time was not considered (aspect “soil-moment”) [5].

The term of general ecology involves the consideration of constant subject-object interaction on a quantitative level. By definition, the soil is an open thermodynamic system that exchanges matter, energy, and information with the environment [1, 6]. The current system of soil fertility reproduction in accordance with the law of nutrients return is based on metabolism with the environment. However, without the other 2 components of the interaction, this system is not effective enough, so now there is a further loss of soil fertility around the world. The exchange of soil with energy for the environment determines the availability of nutrients for plants in the vector of soil–plant–atmosphere. And plants in the production process are guided by the rule of minimizing the cost of their own energy consumption. In fact, the study of the energy interaction of soil with the environment began at the beginning of the last century, with the formation of E. Buckingham of the concept of moisture potential [7], and the V.G. Korneev's invention of the equipment for measuring the force of moisture retention in unsaturated soil – tensiometer [8]. The soil water holding capacity determines the availability of moisture for the roots of plants as the main nutrient, through which all water-soluble compounds are consumed. The availability of moisture to plants can be equated with the availability of nutrients from the soil.

The exchange of soil with the environment is practically not studied, it is a kind of *terra incognita*, although scientists have paid attention to this aspect in the last century [9]. Only due to the formation in the 70–80 years of the last century of the young scientific discipline – synergetics formulated the conceptual foundations of information interaction of soil with the environment, in particular the transfer of related information due to soil regimes and its accumulation in the soil in the form of negentropy – negative entropy [10, 11]. Stability of the soil

system due to the law of accumulation of information: the more information in the system, the more resistant it is to external factors.

Thus, the creation of the theory of soil agrogenic evolution and the theory of soil fertility management are impossible without considering the exchange of soil with the environment not only matter but also energy and information.

The purpose of the research is to substantiate the dynamic functional model of the thermodynamic system of the soil in interaction with cyclic environmental factors, the disclosure of internal homeostatic processes, the result of which is the reproduction of soil structure.

Research methods. Theoretical research, systems analysis and synthesis using synergetics tools, experimental laboratory experiments involving thermodynamic hydrophysical methods.

Research results. The priority in soil ecology is the need to establish a mechanism of external climatic conditions action on the energy state of the heterogeneous soil system. External thermodynamic parameters: temperature ($T^{\circ}C$), atmospheric pressure (R_{atm}), and moisture (θ) (precipitation) are distributed in the soil environment from the soil surface in the form of thermal and humidification waves namely have a structure gradient. The thermodynamic state (potential) of a three-phase heterogeneous system of soil can be determined at any stage. However, the best to determine it is in the liquid phase, due to the moisture potential [8], which depends on the configuration of the water body, bounded by the interface "solid particles–liquid" and "liquid–air" and determines the level of surface energy in the system. It is these interface surfaces that determine the fundamental property of the soil – its **heterogeneity**. Another fundamental property is its **hysteresis**, which is manifested in the ambiguity of the relationship between moisture saturation and the strength of the water holding capacity of the soil [12]. A clear explanation of the physical essence of the phenomenon of capillary hysteresis was obtained on the basis of the proposed model of the soil pore space in the form of corrugated equivalent capillary [13], which justifies the presence in the expansion of the pore space of compressed air, which may be in equilibrium. There is always trapped air in the soil, the amount of which depends on the structure of its pore space and moisture saturation and can be tens of percent of the soil volume. The most important thing is that the air concentrated in the entire volume of the soil environment and with the change of external thermodynamic parameters reacts by changing its volume and gas pressure. In fact, this compressed air acts like a micropump and it becomes a dispersed center of thermodynamics imbalance (CTI), from which moisture can be squeezed out or, conversely, enter the body of the pore. That is, radial gradients are periodically created in the CTI environment, which leads to a local centrifugal redistribution of moisture in the soil. In fact, when interacting with changing external climatic factors, the soil becomes a micro gradient structure with periodic local redistribution of matter, where the trapped air plays the role of a propellant, a kind of "heart" of the mobility of the pore solution. Synergism of interaction of these microzones can lead to changes in the thermodynamic state of the soil at the level of the macroparameter of the system.

Particular attention should be paid to the local redistribution of the pore solution in the environment of the CTI, which convectively transports various compounds. Such a transport mechanism was lacking in theories of humus formation [14] and concepts of structure formation [15]. Another feature of air compression is that with increasing gas pressure in the bubble, it begins the diffusion of gases that make up the soil atmosphere. Its content of carbon dioxide (CO_2) is an order of magnitude higher than the open atmosphere up to 3–20 %. This gas has the highest solubility in the pore solution and, dissociating, increases the concentration of hydrogen ions, and namely increases the acidity of the pore solution (pH) in the environment of the trapped air in certain periods. That is, the CTI periodically becomes an acid center (AC), near which centrifugal acidity gradients (pH) are created. Acidity is a determining factor of phase equilibrium for compounds sensitive to this parameter. Thus, in the environment of CTI+AC the is locally **disturbed the phase of equilibrium**, which together with the local mobility of pore solutions creates conditions for a certain spatial selection and zoning of compounds centrifugally from compressed air and unique opportunities to change the volume of elementary pores due to relative movement of excess gas pressure which release from the cement of dispersed particles that make them consist. An ecotone of the soil microbiota is also formed around the bubbles of compressed air in accordance with the radial zonation of the ecological conditions of their soil life.

The concept of an **active kinetic environment** is key for synergetic [16], and the soil fully corresponds to it. It has a distributed source of energy and/or energy-rich substances; each elementary volume of the medium is in a state far from thermodynamic equilibrium; communication between adjacent elementary volumes is carried out through exchange processes.

The priority for the soil is the question of the availability of a distributed energy source. Organic matter is an energy reservoir, which is slowly released into the soil during its biochemical decomposition and actually determines its energy efficiency. However, the kinetic component of the energy balance of the soil is many times greater than the energy content of organic matter in it and depends on the level of dissipation of solar energy, which is determined by the intensity of energy-consuming subordinate soil processes. Such processes ensure the homeostasis of the soil, the result of which is the reproduction of a certain structure and high humus content.

Soil structure. In modern agrophysics, there is no concept of elementary volume as the level of organization of soil mass [17]. However, its presence is fundamental for thermodynamic and synergetic. In agrophysics, the structure of the soil is understood as a set of features, aggregates, different in size, shape, strength, and coherence [15], characteristics of each soil, and its horizons. However, this approach to assess the structure of the soil as a highly organized system is incorrect, because the ratio of fragments is a function of the method of violation and many other factors (temperature, humidity, etc.). The most important thing is that the synergy of the interaction of all components of dispersed soil elements is not taken into account. Plant interacts with the soil as a whole system, and the availability of food is due to the potential of moisture as an integrative concept of the

three-dimensional structure of the soil. Therefore, thermodynamic methods should be used to characterize the structure of the soil.

The fundamental property of soil is its heterogeneity, which is integrally characterized by the surface areas of the section “solid particles–liquid” and “liquid–air”. An integral characteristic of the **structure of soil composition is the structure of its pore space**, which determines through the surface tension of the liquid surface energy and variable bond strength of moisture with the frame soil, namely its capillary potential. This functional dependence of the capillary potential on the moisture saturation $P = f(\theta)$ is called the curve of the soil water holding capacity, or its main hydrophysical characteristic (MHC) [18]. In fact, the MHC is an integral curve of the distribution of the pore space of the soil by size – the radii of the inscribed sphere in the imaginary capillaries. However, taking into account the irregularity of the intersection of imaginary capillaries in a real dispersed medium, the pore space can be characterized by 2 characteristic dimensions – r_{\min} and r_{\max} [19]. These radii correspond to the radii of the inscribed sphere at the narrowest point of the body of the pore r_{\min} and at the extensions of the pore – r_{\max} . It is these radii of curvature of the pore solution that determine the capillary pressure during drying and filling of the pore body during sorption and desorption, which is the cause of capillary hysteresis.

The proposed physical model of the pore space in the form of a corrugated equivalent capillary takes into account the irregularity intersection of the pore space and characterizes integrally the volume of all capillaries due to the curvature of the equivalent capillary [19]. In the expansions of the pore space, the trapped air can be in the equilibrium state, where the condition $r_{\max} \geq r_a \geq r_{\min}$ is fulfilled and where r_a is the radius of the generalizing meniscus of the liquid in contact with the atmosphere [13]. In this case, the surface area of the interface is liquid–air, connected with the atmosphere, which is appropriate to call **extraheterogeneity**, the surface area of the liquid–air interface in the bubbles of compressed air is added, which can be called intraheterogeneity. That is, the structure of the pore space of soil unsaturated with moisture at any time is limited by the interface of extra – + intraheterogeneity. This is the relationship of 2 fundamental properties of the soil – **heterogeneity, and hysteresis** [4, 12].

In fig. 1 shows the results of a laboratory experiment on the effect of a thermal pulse on the dynamics of the capillary potential of an isolated sample of loess species of constant moisture saturation. It is the loess soil that is the main parent rock on which the most fertile of Chernozem soils of Ukraine are formed.

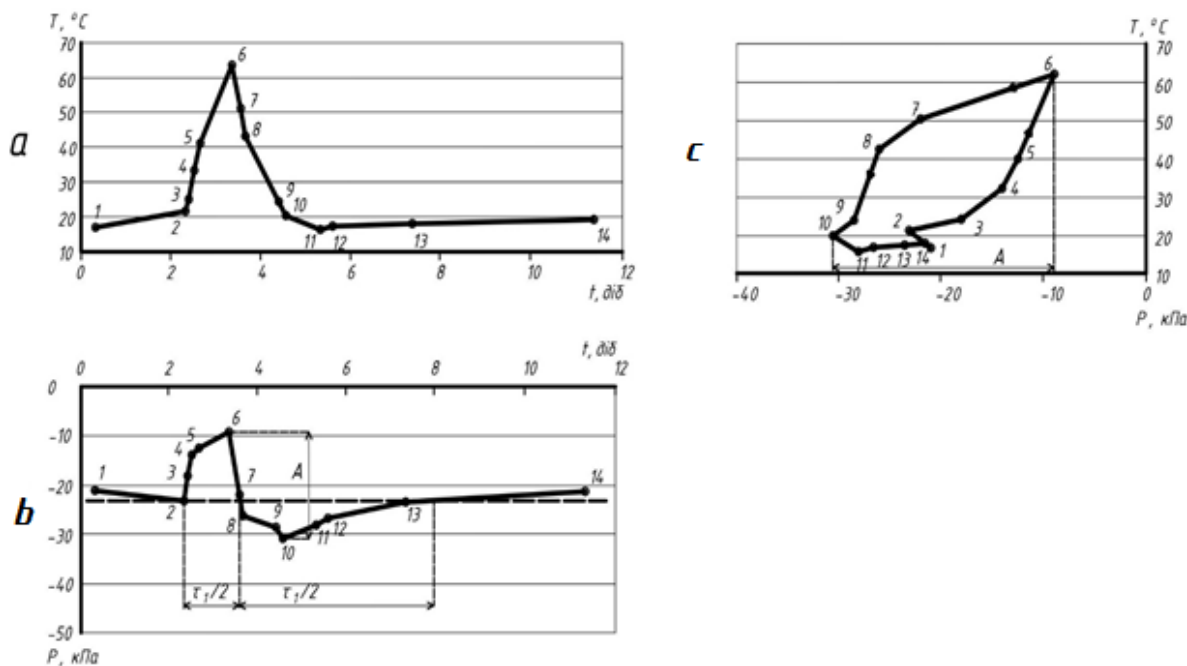


Fig. 1. Dynamics of redistribution of moisture in the pore space of the loess soil for sustainable moisture content ($\theta = \text{const}$) under the influence of temperature: a – chronological graphs of the samples, $T^{\circ}\text{C} = f(T)$; b – the capillary potential of moisture in soil $P = f(t)$; c – a loop of temperature hysteresis of capillary moisture potential $P = f(T^{\circ}\text{C})$

The experiment was as follows: a cylindrical sample of forest-like species of the disturbed structure of constant humidity $\theta = \text{const}$ with a volume of 10 dm^3 , isolated from moisture exchange with the atmosphere (connected for gas exchange with it only through a labyrinth), was equipped with a tensiometer. Soil temperature was monitored by laboratory thermometers directly next to the tensiometer. The soil was heated in a water bath from 20 to 60 $^{\circ}\text{C}$, which corresponds to the range of natural variability of soil temperature, after which it was slowly cooled in the atmosphere for several days.

The result of the thermal impulse (Fig. 1, a) was the autolysis process of changing the capillary potential of the soil sample for sustainable moisture content (Fig. 1, b). This process can be explained by an essential change in intraheterogeneity in accordance with the adopted model of the corrugated equivalent capillary [13]. Since the heating is avalanche-like closure of liquid membranes of pores of increasing size due to the gratification of the

foam solution from elementary pores with bubbles of pinched air, which increases the volume and decrease the surface tension of the ferry solution itself with the growth of temperature. That is, the intraheterogeneity of the soil sample and its surface energy increases significantly. This process depends on the rate of growth of the soil sample since it generates an opposite process is a violation of equilibrium and dissolving the clamped air in the smallest pores where $r_a \gg r_{max}$. This leads to priority dissolution in these pores of air, because excessive gas pressure they are determined by the radius difference of curvature of the meniscus [13]. With a decrease in heating speed, the effect of these opposite processes is balanced, the capillary potential reaches its maximum, and with the beginning of cooling begins the reverse process of avalanche disclosure of pores of the greatest radius with the corresponding decline in capillary potential. Since the smallest pores of the air have already dissolved, the capillary potential passes the initial values and continues to decrease to a value lower than 10 kPa. Then the half-period of relaxation begins is a slow restoration of equilibrium state. In this case, the amplitude of the potential dynamics (a) was 21.5 kPa.

In general, the intensity of such subordinate homeostatic processes in the soil arising from the variability of external thermodynamic parameters is determined by the structure of the thermodynamic system, that is, the structure of pavement space (SPS); the presence of moisture as a "working body" in the system; the intensity of the variability of external thermodynamic parameters.

Daily fluctuations of soil temperature can reach a depth of 50–70 cm. The most likely plants went through adaptation of physiological cycle of consumption to the laws of the daily cycle of dynamics of moisture potential in the soil under the action of daily fluctuations of external parameters.

The conservative characteristic of the soil bulk structure is its MHC. However, the most informative is the loop of capillary hysteresis of MHC, obtained in rapid desorption mode from maximum hygroscopic moisture (MGM) and slow equilibrium sorption (Fig. 2). Such a loop should be considered as a diagram of a thermodynamic state that combines the capacitive properties of real soil (θ) with capillary potential (P) and includes an area of tolerance of variable values of moisture potential in accordance with the variability of external perturbations. After all, the rapid desorption curve from MGM $\theta = f(P)$ is obtained in the absence of pinched air in the soil, and the equilibrium curve of slow sorption characterizes the contents of the clamped air in the expansion of the pores provided equilibrium: $r_{max} \geq r_a \geq r_{min}$. The difference in moisture content $\Delta\theta$ on the branches of sorption and desorption for fixed values of capillary potential ($P = \text{const}$) characterizes the total volume of clamped air in a group of pores, where equilibrium conditions are performed. From the capillary potential of Zhuren's formula it is easy to move to the radiuses of porosity: $r \approx \frac{0.15}{P, \text{cm water pillar}} [\text{cm}]$. The curve of the so-called structural characteristic $V_{ZP} = f(P)$, or $V_{ZP} = f(r)$ characterizes the peculiarities of the structure of the pore space of different types of soils, which was experimentally investigated in hundreds of samples and is an important diagnostic feature (Fig. 2, b). It has been experimentally confirmed that this curve responds sensitively to spatial and time epigenetic rearrangements of the structure of the pore space under the action of changing the homeostasis of the soil of any origin in real-time, providing a quantitative comparison of the structure of the soil. The accuracy of the production of desorption curves and sorption in repeats is typically $\pm 0.5\%$ by soil moisture. Should pay attention to the fact that for point $P = 0$ according to Zhuren's formula, arises uncertainty, because $r = \infty$, so experimentally the curve of equilibrium sorption does not prove to the values $P = 0$. Repeated desorption begins with values $P = -0.5$ kPa [20].

The scope of the hysteresis loop by capillary pressure (ΔP) for sustainable moisture values ($\theta = \text{const}$) integrally determines the characteristic dimensions of porosity: r_{min} on fast desorption curve and r_{max} on the equilibrium sorption curve. If for modeling environments correlation $n = \frac{r_{max}}{r_{min}} = 1,77 \div 1,86$, characterizes elementary porosity, then in real soil taking a limiting ratio $n = \frac{r_{max}}{r_{min}} \geq 2$ exceeding $n > 2$ characterizes the development of macroporousness (Fig. 2, c). Such a determination of threshold values of macroporous in soils is more reasonable, especially for soils of various dispersion than available in modern agro-physics, the practice of determining the macroporous size. Building on the basis of a loop hysteresis graphics of the values $n_i = f\left(\frac{r_{sorb}}{r_{desorb}}\right)$ characterizes the integral ratio of characteristic porosity dimensions, which uniquely establish the threshold size of the macroporous development by value $n = 2$. In well-structured soils, in particular, Chernozem soil, the value of n , according to the testing, may acquire several dozen.

In fig. 2, and the curve of rapid desorption from MGM is the most informative. It is believed that it is obtained in the absence of trapped air in the soil. Any changes in moisture saturation, depending on the speed of the process, deviate from the current state of the capillary potential (P_i) from this equilibrium curve to the right for soil moisture (from point 1 to point 2). When humidification stops, the capillary potential slowly returns to the equilibrium curve (from point 2 to point 3). With the onset of desorption, depending on the speed of the process, the current state (P_i) deviates to the left of the equilibrium curve toward the rapid desorption curve (from point 3 to point 4). The suspension of the desorption process returns the current values of P_i to the equilibrium curve (from point 4 to point 5). Changes in temperature and atmospheric pressure also deviate the current values of P_i from the equilibrium sorption curve. The deviation of the values to the right of the equilibrium curve reflects the half-life of the soil to external factors, which is the most productive to ensure the thermodynamic availability of the pore solution, namely improving the productive function of the soil. And it provides the process of uneven cementation of mineral elements of the soil, which forms the embryos of structural units. The relaxation half-life, which causes the deviation of the current values of P_i to the left of the equilibrium curve, has not yet been considered, and this requires further experimental studies. From the fast desorption curve to the ordinate axis there is a region (plateau) of tolerance (II), where the current values of P_i can be. To the left of the rapid desorption curve and to the right of the ordinate axis is the bifurcation region (I), at the exit of the values of R_i to which

unpredictable processes of restructuring or violation of soil integrity can occur. To the left of the rapid desorption curve, a high desorption rate can reduce the pore volume, as is the case, for example, within the capillary zone on drained lands with sharp fluctuations in the groundwater level (GWL). To the right of the ordinate axis R_i acquire positive values, from which the soil can turn into a thixotropic state.

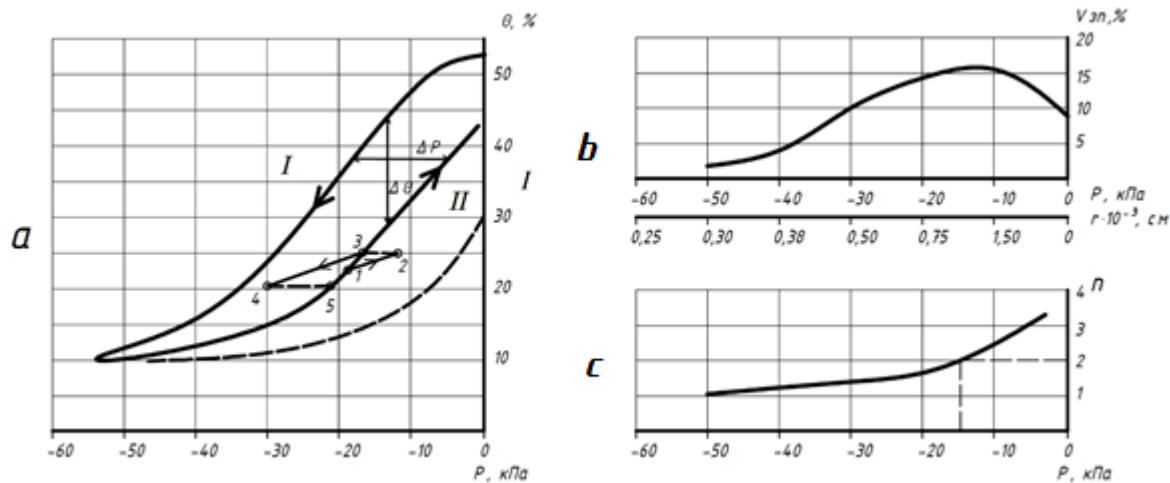


Fig. 2.

Experimental hydrophysical tests of soil samples: a – hysteresis diagram of the thermodynamic state of real soil; b – structural characteristics of the pore space $V_{zp} = f(r)$; c – the curve of the ratio of the characteristic dimensions of the porosity; $n = r_{max} / r_{mix}$; I – area of bifurcation, II – area of tolerance

Thus, soil homeostasis performs a number of functions and contains a set of energy-intensive microprocesses in the environment of macropores with compressed air, which arise under the action of cyclically changing external conditions in the form of local centrifugal circulation moisture flows with phase transitions. They provide selection and zoning in space of compounds sensitive to acidity pore solution, creating reversible uneven cementation of dispersed particles, which during soil disturbance provides disintegration into macropores and forms structural features of different shapes and sizes depending on the mutual location of macropores. Homeostasis implements a dual function of the soil: productive to ensure periodically increased in space and time availability for plants of food components and ecological - to preserve and accumulate components nutrition in the structure of the soil matrix.

Conclusions

The interaction of soil with thermodynamic environmental factors transforms it into a microgradient dissipative structure with the emergence of a number of subordinate energy-consuming microprocesses. A special role in ensuring the high energy efficiency of the soil belongs to water as a “working body” in the thermodynamic system of the soil. Because of the centers of thermodynamic imbalance, acid centers and centers of ecotones become the clamping in the expansion of the pore space by liquid air membranes, which begin to respond to changes in external environmental parameters.

The main results of mainly diurnal cyclic action of subordination processes are periodic local increase thermodynamic availability of nutrients for plants and the formation of uneven in space cementation of dispersed particles that become the embryos of structural units.

The concept of soil homeostasis, combining subordination processes, characterizes the level of energy consumption by the soil of the external energy flow, due to which the basic properties, structural organization, and productive function are reproduced. The research resulted in new knowledge and the latest methods of diagnosing soils.

References

1. Furdychka, O.I. (Ed.). (2007). *Slovnnyk-dovidnyk z ahroekolohii* [Dictionary-reference book on agroecology] Kyiv: Osnova [in Ukrainian].
2. Volobuev, V.R. (1963). *Ekologiya pochv (ocherki)* [Soil ecology (essays)]. Baku: AN Azerb. SSR. [in Russian].
3. Dobrovolskiy, G.V., & Nikitin, Ye.D. (1986). *Ekologicheskie funktsii pochvy* [Ecological functions of the soil]. Moskva: MGU. [in Russian].
4. Nadtochii, P.P., Myslyva, T.M., & Volvach, F.V. (2010). *Ekolohiia irtuntu* [Soil ecology]. A monograph. Zhytomyr: PP Ruta [in Ukrainian].
5. Targulyana, V.O., & Goryachkina, S.V. (Ed.). (2008). *Pamyat pochv: pochva kak pamyat biosferno-geosferno-antropogennykh vzaimodeystviy* [Memory of soils: soil as a memory of biosphere-geosphere-anthropogenic interactions]. Moskva: LKI. [in Russian].
6. Reymers, N.F. (1990). *Prirodopolzovanie. Slovar-spravochnik* [Nature management. Reference dictionary]. Moskva: Mysl. [in Russian].

7. Shevchenko, O.L., Bubljas, V.M., & Kolomiets, S.S. (2014). *Osnovy perenesennia volohy v zoni aeratsii* [Fundamentals of moisture transfer in the aeration zone: textbook] Kyiv: Kyivskiy universytet [in Ukrainian].
8. Kornev, V.G. (1925). *Vsasyvayushchaya sila pochvy i printsipy systemy avtomaticheskogo orosheniya pochvy* [Soil suction power and principles of the automatic soil irrigation system]. Moskva: Izdanie GISKhM. [in Russian].
9. Perelman, A.I. (1977). *Biokosnye sistemy Zemli* [Bioinert systems of the Earth]. Moskva: Nauka. [in Russian].
10. Prigozhin, I.R. (1980). *Vremya, struktura i fluktuatsiya: Nobelevskaya lektsiya po khimii 1977 goda. Uspekhi fizicheskikh nauk* [Time, structure and fluctuation: The 1977 Nobel Lecture in Chemistry. Advances in physical sciences], 131, 2, 185 – 207. [in Russian].
11. Khaken, G. (1985). *Sinergetika: ierarkhiya neustoychivostey v samoorganizuyushchikhsya sistemakh i ustroystvakh* [Synergetics: a hierarchy of instabilities in self-organizing systems and device. Moskva: Mir. [in Russian].
12. Nadtochii, P.P., Volvach, F.V., & Hermashenko, V.H. (1989). *Ekolohiia gruntu ta yoho zabrudnennia* [Soil ecology and its pollution]. Kyiv: Ahrarna nauka [in Ukrainian].
13. Kolomiets, S.S. (1999). Ekolohichna kharakterystyka gruntu [Ecological characteristics of the soil]. *Bulletin of Agricultural Science*. Kyiv, 12, 9 – 13. [in Ukrainian].
14. Fedotov, G.N., & Shoba, S.A. (2013). Sushchestvuyushchie predstavleniya o vozmozhnykh putyakh formirovaniya gumusovykh veshchestv v pochvakh [Existing ideas about possible ways of formation of humic substances in soils]. *Soil Science*, 12, 1523 – 1529. [in Russian].
15. Panasenko, O.S. (V.V. Dehtiarova (Ed.)) (2015). *Humus strukturnykh ahreativ chornozemiv typovykh pryrodnykh i ahrohennykh ekosystem: monohrafiia* [Humus of structural aggregates of chernozems of typical natural and agrogenic ecosystems: monograph] Kharkiv: Maidan. [in Ukrainian].
16. Druzhinin, D.L., & Vanyarkho, V.G. (1989). *Sinergetika i metodologiya sistemnykh issledovaniy. Sistemnye issledovaniya. Metodologicheskie problemy. Yezhegodnik* [Synergetics and methodology of systems research. Systemic research. Methodological problems. Yearbook]. Moskva: Nauka. [in Russian].
17. Dobrovolskiy, G.V. (1999). *Strukturno-funktsionalnaya rol pochvy v biosfere: monografiya* [Structural and functional role of soil in the biosphere: monograph]. Moskva: GYeOS. [in Russian].
18. Globus, A.M. (1969). *Eksperimentalnaya gidrofizika pochv* [Experimental hydrophysics of soils]. Leningrad: Gidrometeoizdat. [in Russian].
19. Lykov, A.V. (1950). *Teoriya sushki* [Drying theory]. Moskva: Gosenergoizdat,
20. Romashchenko, M.I., Kolomiets, S.S., & Bilobrova, A.S. (2019). Systema laboratornoho diahnostuvannia vodno-fizychnykh vlastyvostei gruntiv [System of laboratory diagnostics of water-physical properties of soils]. *Land reclamation and water management Kyiv*, 2, 199 – 208. doi:10.31073/mivg201902-193 [in Ukrainian].