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THERMODYNAMIC ASPECTS OF THE GEOSYSTEM FUNCTION OF THE PEDOSPHERE

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Abstract. *Modern unceasing processes of dehumification and degradation of arable soils require the search for new non-traditional approaches to solving this global environmental problem, which determines the relevance of the research. After all, plowing significantly disrupts the thermodynamic interaction of the soil with environmental factors. The purpose of the publication is to consider the regularities of the evolution of the properties of the pedosphere from a geosystem perspective, to define the concept of geomembrane properties, and to reveal the mechanism of regulating the thermodynamic interaction of the soil with the environment based on the concept of its homeostasis, which will allow a more reasonable explanation and forecast of modern evolutionary changes in the properties of soils and soil cover from a higher perspective organizational level of the geosystem. The main tasks are defined as: the development of a methodology for studies of the thermodynamic interaction of soil with climatic factors, the creation of tools for monitoring the course of thermodynamically unbalanced processes in the soil environment, and their approbation in the Forest-Steppe zone of Ukraine. It is proposed to consider the soil as a dissipative thermodynamic non-equilibrium system that is constantly in the process of self-stabilization and self-organization due to interaction with climatic factors of the environment. Therefore, soil homeostasis means the presence of subordinate energy-consuming processes of a certain intensity, which form the structure of the thermodynamic system of the soil, as the structure of its pore space. It was determined that the general direction of the development of the pedosphere, as an element of the Earth's lithospheric shell, is the densification of the parent rock with the formation of structural macroporosity of the soil and the development of heterogeneity. It is shown in the example of Ukraine, that the geomembrane properties of soils have a zonal nature and aimed at limiting the power of the zone of active energy-mass exchange. The concept of the dynamics of geomembrane properties of the pedosphere, as a manifestation of a higher hierarchical level of geosystem organization, is proposed to be used to solve purely applied issues, such as assessing the impact of climate change, humus formation, and modern dynamics of soil fertility, increasing the sustainability and ecological safety of soil use.*

Keywords*: pedosphere, soil, thermodynamic system, dissipation, pore space structure, energy efficiency of interaction, soil homeostasis*

Topicality. The pedosphere is the part of the Earth's lithospheric shell bordering the atmosphere, which experiences the strongest influence of external factors that determine the most intensive processes of soil reconstruction and self-organization. According to the Le Chatelier-Braun principle, a system capable of self-stabilization and self-organization changes its properties in a direction that limits the penetration of external disturbances into the system [1]. In fact, the pedosphere regulates the exchange flows of the Earth's lithosphere with the atmosphere and space. However, the most important aspect is the regulation of the thermodynamic interaction of the pedosphere with the external environment, which determines the direction of its self-organization processes and biosphere properties and gives grounds for considering the soil as a thermodynamic system, the functioning of which is determined by the thermodynamic interaction with the environment.

Analysis of recent research and publications. Although the concept of soil moisture potential was formulated by E. Buckingham at the beginning of the last century [2], and in the practice of reclamation agriculture, the potential characteristic of soil moisture has been used to control the water regime for decades, but until now the soil has not been considered as a complete thermodynamic system. After all, the postulates of classical equilibrium

thermodynamics are unsuitable for displaying processes in a permanently thermodynamically unbalanced system of the soil environment. Attempts to establish the relationship between soil properties and classical thermodynamic functions – Gibbs potential and entropy – were very time-consuming and not sufficiently effective [3]. And only after the formulation in the period the 70s to 90s of the provisions of synergetics, which deals with the theory of self-organization of complex thermodynamically unbalanced systems [4; 5], at the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine (IWPLR NAAS), an attempt was made to consider the soil as an integral thermodynamic system.

The purpose of the publication is to consider the regularities of the evolution of the properties of the pedosphere from a geosystem perspective, to define the concept of geomembrane properties, and to reveal the mechanism of regulating the thermodynamic interaction of the soil with the environment based on the concept of its homeostasis, which will allow a more reasonable explanation and forecast of modern evolutionary changes in the properties of soils and soil cover from a higher perspective organizational level of the geosystem.

Research methods. From the point of view of synergy, the soil is identified as a dissipative active kinetic environment in which flows of matter, energy, and information are transformed [6]. Therefore, it is proposed to characterize the soil as a microgradient dissipative structure, in which a special role belongs to macropores with air trapped by liquid membranes, which actively reacts to changes in external thermodynamic parameters of temperature (T, °C), atmospheric pressure (R_{atm}) and moisture saturation (θ_{vol}) by changing its volume and gas pressure. As a consequence of this, macropores become centers of thermodynamic imbalance (CTI), acid centers (AC), and centers of formation of ecotones of soil biota, around which periodically centrifugal gradients of moisture potential and gradients of solution acidity are observed, which causing reciprocating movements of substances with phase transitions. Such energy-consuming subordinate (internal) processes are actually processes of soil formation. This allows to state that soil formation processes occur in the pedosphere everywhere and all the time, and the soil, which genetic soil science defines as a natural-historical body that has constant properties on a real-time scale, actually is a dynamic thermodynamically unbalanced system that is constantly in the process of self-stabilization within the tolerance plateau of external factors, and self-organization when external factors go beyond the tolerance plateau, for example, global climate change. This approach allows substantiates the concept of soil homeostasis, which is determined by the level of consumption (dissipation) of external flows of energy and matter due to energy-consuming subordinate processes of a certain intensity [7]. An eloquent example of the impact of a change in the level of soil homeostasis is the formation of the so-called compacted "plow sole" in the subsoil horizon of soils which used in agriculture. This negative ecological phenomenon of agriculture is actually a systemic reaction of the soil environment to the reduction of soil homeostasis in the subsoil horizon due to damping of the amplitude of temperature and soil moisture fluctuations in the loosened arable layer. This plow sole is formed during the first decades after plowing. And although in agrophysics it is believed that this phenomenon is the result of an increase in the weight of tillage aggregates, in fact, the formation of a plow sole is a reaction to plowing, and an increase in the weight of aggregates can only be a tool for transitioning to a new level of dynamic balance. Failure to use a plow destroys this plow sole over time [8].

Soil homeostasis determines the energy efficiency of soil interaction with the external environment and depends on three components which are the design of the thermodynamic system; the available moisture in it, as a working element, due to which subordinate processes are implemented; the intensity of variability of external thermodynamic factors [7]. To characterize the design of the thermodynamic system, in contrast to the traditional determination of soil structure in agrophysics through the ratio of soil fragments based on granulometric, aggregate, and microaggregate analysis, it is proposed to use its pore space structure (PSS), which reflects the heterogeneity of the environment. With using of a physical model of the capillary porosity of the soil in the form of a corrugated equivalent capillary, the "Method of determining the structure of the pore space of soils (dispersed media)" was developed in IWPLR NAAS [9]. This method is based on the study of the capillary hysteresis loop of the water-holding capacity of the soil. Using it as a research tool made it possible to establish the regularities of spatio-temporal variability of PSS in soils of different genesis, which is characterized by the so-called structural characteristic, which is essentially a differential curve of the distribution of the volume of pore space by porosity radii (Fig. 1) [7]. The PSS is a sensitive tool for monitoring epigenetic changes of pore space in different types of soils, both for irrigation and drainage conditions. If for most soil types the structural characteristic has an

extremum, which indicates the presence of pores of a predominant size in them, then for the most fertile chernozem soils this structural characteristic has the form of a monotonically increasing curve. This indicates the development in chernozems of the volumetric structure of the three-dimensional soil matrix, in which the largest volume belongs to the largest macroporosity. This PSS curve is proposed as a benchmark for the development of soil formation, according to which it can be argued that the general progressive development of soil formation is the densification of the parent rock with the formation of macroporosity resistant to external factors. Degradation processes of these soils begin with a decrease in the volume of this very largest porosity, which was recorded, for example, on irrigated chernozems due to non-compliance with scientifically based irrigation regimes.

A system of complex laboratory diagnostics of water-physical properties of soils has been developed and successfully tested at the IWPLR

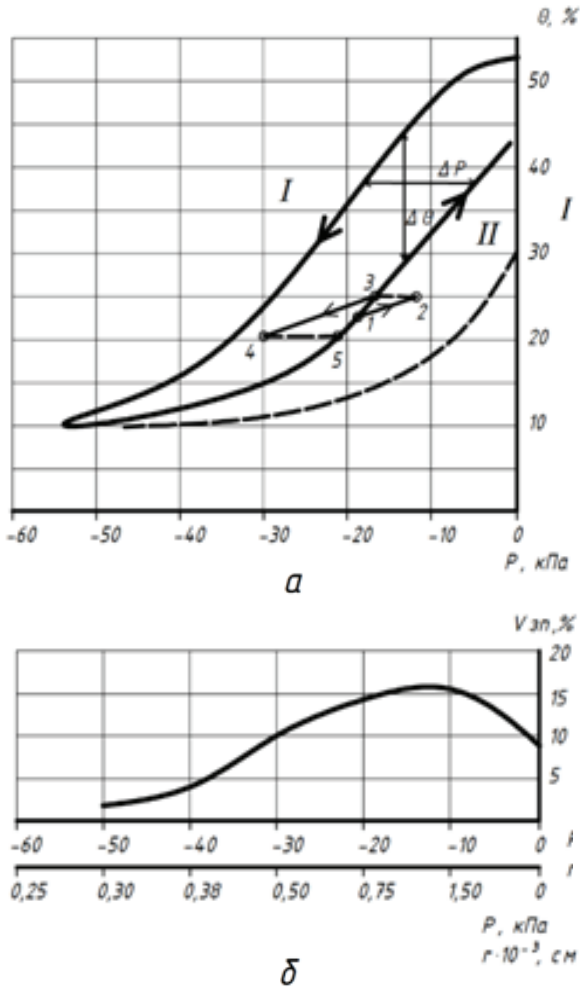

Fig. 1. Hysteresis diagram of soil water-holding capacity (a); structural characteristic of the pore space $V_{зп} = f(r)$; I – bifurcation area, II – tolerance area [7]

NAAS [10]. In particular, the regularities of PSS in the soil profile approaching the ground surface were established. The result of soil formation is a natural decrease in the volume of elementary pores of the predominant size, but an increase in the size (radii) of this predominant porosity [11]. For hydromorphic conditions of soil formation, it was found that the volume of a certain group of pores decreases in the capillary border, until it completely disappears, due to the lack of their self-development due to capillary filling with water. According to the depression of the structural characteristic, it is even possible to identify the weighted average position of the groundwater level, relative to the depth of sample selection, with an accuracy of up to 10 cm [12]. However, the structure of the soil pore space is derived from the diagram of the thermodynamic state, which combines the capacitive properties with the power of stabilizing moisture in the soil (Fig. 1), and the most informative is the capillary hysteresis loop obtained in a special mode. Therefore, from the geosystemic point of view, the thermodynamic interaction of the soil with the environment is regulated by the construction of the three-dimensional soil matrix, which combines such fundamental properties as heterogeneity and hysteresis. Using the example of chernozem, it can be concluded that the implementation of geomembrane properties to limit the penetration of external disturbances deep into the soil profile is ensured by the growth of water-holding capacity and hysteresis, which generally reduces the conductivity parameters of the soil environment, primarily for moisture flow, but increases its dissipativeness in relation to energy flows. Enrichment of chernozem with free types of surface energy ensures its high fertility.

Research results and their discussion. Characterized for chernozem soils PSS, as a design of a thermodynamic system, ensures a high intensity of subordinate processes by dissipating external flows in the soil, which creates increased availability of nutrients from the soil to plants, i. e. is a determining factor of soil fertility. In fact, the energy efficiency of soil interaction with climate factors has a direct correlation with soil fertility, and the production process is considered as the utilization of external energy by plants according to their own genetic program. An important role in these processes is played by the symbiosis of the mineral component of the soil with organic matter, in particular, the accumulation of humus, which should primarily be considered not as a chemical formation, but as a thermodynamic process of qualitative ordering (assembly) of high-molecular organic compounds in conditions of cyclic washing of low-molecular compounds by subordinate

processes. However, it is no less important that the accumulation of humus in the soil transforms it from a purely capillary body into a colloid-capillary body, in which the mobility of moisture is significantly limited. After all, moisture is removed from the colloidal body mainly through evaporation. This is seen as one of the mechanisms for the formation of geomembrane properties of soils and the pedosphere in general – limiting the penetration of external thermodynamic disturbances, in particular moisture flows, deep into the Earth in the radial direction. The process of densification of the parent rock with the formation of stable structural macroporosity also limits the thermal conductivity parameters and the depth of active energy-mass exchange in the soil environment.

Experimental monitoring studies of soil regimes up to a depth of 5.0 m using thermodynamic hydrophysical methods in the soil-geochemical chain from the watershed to the floodplain of a small river were conducted in the Obukhiv district of Kyiv region (Forest-Steppe zone) in the period of 1989–2005 [13]. These studies made it possible to establish a regular spatial variability of the geomembrane properties of the soil cover, which is characterized by a set of indicators such as the infiltration nutrition and seasonal dynamics of moisture reserves, the chemistry of pore solutions, the structure of the pore space of soils and the level of their fertility, etc. The highest development of the geomembrane properties of soils is established in the plakor part of the watershed which is characterized by the zone of active energy mass exchange did not exceed 3–4 m, because at this depth the mineralization of pore solutions of chloride-sulfate composition increased to 3–5 g/dm^3, infiltration nutrition is virtually absent, the automorphic mode of soil formation, the growth of the soil profile occurs due to atmospheric dust deposition, so here is the most complete section of the holocene with the presence of humus buried soils. The realization of geomembrane properties occurs due to the loosening and growth of soil heterogeneity and its humus content. On the slopes which are characterized by the zone of active energy-mass exchange exceeding 5 m, there is a periodically washing water regime, and the development of PSS is relatively lower due to water erosion and planar washing of fine soil, the processes of epigenetic restructuring of PSS is activated in the entire soil profile, in particular, at its lower border in the parent rock, soil fertility is reduced, the chemistry of pore solutions is hydrocarbonate-calcium with mineralization up to 1 g/dm^3. In the floodplain of a small river which is characterized by the effluent water regime with fluctuations of soil water levels from 0.0 to 2.0 m, which determines the zone of active energy-mass exchange, and the realization of geomembrane properties, in particular, from limiting the depth of active water exchange, is ensured by magnesium-sodium salinization, PSS is characteristic of hydromorphic soils.

In addition to the variation of geomembrane properties within the Forest-Steppe and the formation of different types of soils (the principle of divergence), it was established that within Ukraine, the formation of geomembrane properties is determined by the degree of balance of moisture and heat flows, and specified the latitudinal zonation of these properties. In particular, in the energy-limited zone of Polissia, the limitation of the zone of active energy-mass exchange ensures the formation of a weakly permeable, unstructured, compacted illuvial (podzolic, glee, etc.) horizon within the first meter of the soil section. This horizon, serving as a pre-surface screen for moisture flows, ensures the discharge of excess atmospheric precipitation by surface runoff. In the conditions of modern climatic changes, which increase the energy supply of the Polissia zone, this illuvial horizon serves as a screen for the reproduction of underground water resources, which leads to their progressive depletion. A radical means of combating such a negative ecological phenomenon for the new climatic conditions in Polissia is the destruction of this illuvial horizon by means of deep meliorative loosening or plantation plowing [14]. Such measures have been practiced in drainage reclamation to accelerate the cultivation of drained soils, which require periodic repetition to maintain a high level of homeostasis (fertility) of these soils. After all, in the drained soils of reclamation systems, which are mainly in the capillary border of groundwater, the disappearance of a certain group of pores due to intense fluctuations of soil water levels, which leads to the compaction of these soils, was found.

For the Steppe zone of Ukraine, the limiting factor of the self-development of the soil and its energy efficiency is the lack of moisture. That is why, in this water-limited zone, irrigation melioration is the most effective for increasing soil homeostasis and fertility.

Therefore, in the Forest-Steppe of Ukraine, with a balanced amount of precipitation and heat, the highest development of the geomembrane properties of the pedosphere is recorded. Accordingly, this zone is the most bioproductive [15]. In the direction of the energy-limited zone of Polissia, the geomembrane properties of the pedosphere are aimed at limiting the depth of active water exchange, and when moving from the Forest-Steppe to the south to the water-limited zone of the Steppe, the geomembrane

properties of the pedosphere decrease due to the insufficient level of soil self-organization, which is limited by the lack of moisture. Such regularities should be taken into account when predicting evolutionary changes in soil properties under the conditions of global climate changes and shifts in the balance of the amount of heat and moisture.

Conclusions. Considering the soil as a complete thermodynamically unbalanced system in interaction with the thermodynamic factors of the environment according to the formulated concept of homeostasis makes it possible to unambiguously evaluate and predict changes in soil properties under global climate changes at any point of the soil environment according to the level of consumption in the subordinate processes of the soil of the kinetic energy of external flows, as a manifestation geomembrane function. A conservative criterion for changing such soil properties is epigenetic changes in the structure of its pore space, as a design of a thermodynamic system, which is characterized by a laboratory-determined loop of capillary hysteresis of water-holding capacity in a special mode.

Constant processes of self-organization and self-stabilization provide a change in the geomembrane properties of the pedosphere, which have a latitudinal zonation and depend on the degree of balance of heat and moisture flows. The highest development of geomembrane properties of the pedosphere, caused by the balance of heat and moisture flows, is observed in the Forest-Steppe zone. Within the energy-limited zone of Polissia, the limiting geomembrane function of the pedosphere is aimed at reducing the penetration depth of water flows. Within the soil-climatic zones, the spatial differentiation of the soil cover according to geomembrane properties is determined by the relief, lateral flows of matter, and other natural and anthropogenic factors that limit the level of soil self-organization.

The level of homeostasis, as the top manifestation of the geomembrane properties of the soil, which has an energetic nature, can be studied by remote methods and can have a direct correlation with fertility parameters.

The application of the concept of geomembrane properties of the soil cover will make it possible to move away from purely stochastic models of spatial distribution and dynamics of soil properties and to increasingly use parametric dynamic deterministic models for modeling geomechanics. In particular, their use in soil rheology is promising. The latitudinal zonality of the development of geomembrane properties determines the latitudinal zonality of the ecological resistance of the pedosphere to pollutants and pollution: the most resistant is the Forest-Steppe zone, which must be taken into account when placing environmentally hazardous enterprises and justifying the zonal coefficient of ecological stability of the soil cover.

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ТЕРМОДИНАМІЧНІ АСПЕКТИ ГЕОСИСТЕМНОЇ ФУНКЦІЇ ПЕДОСФЕРИ

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Анотація. *Сучасні невпинні процеси дегуміфікації та деградації орних ґрунтів вимагають пошуку нових нетрадиційних підходів до вирішення цієї глобальної екологічної проблеми, що й визначає актуальність дослідження. Адже оранка суттєво порушує термодинамічну взаємодію ґрунту з чинниками довкілля. Метою публікації є розгляд закономірностей еволюції властивостей педосфери з геосистемних позицій, визначення поняття геомембранних властивостей та розкриття механізму регулювання термодинамічної взаємодії ґрунту з довкіллям на основі поняття його гомеостазу, що дозволить більш обґрунтовано пояснювати і прогнозувати сучасні еволюційні зміни властивостей ґрунтів і ґрунтового покриву з позицій більш високого організаційного рівня геосистеми. Основними завданнями визначено: розроблення методології досліджень термодинамічної взаємодії ґрунту з кліматичними чинниками, створення інструментарію для контролю перебігу термодинамічно нерівноважних процесів у ґрунтовому середовищі та їхня апробація у зоні Лісостепу України. Запропоновано розглядати ґрунт як дисипативну термодинамічну нерівноважну систему, що постійно перебуває у процесі самостабілізації і самоорганізації за рахунок взаємодії з кліматичними чинниками довкілля. За цього під гомеостазом ґрунту розуміється наявність субординаційних енерговитратних процесів певної інтенсивності, що формують конструкцію термодинамічної системи ґрунту, в якості якої прийнята структура його порового простору. Визначено, що загальним спрямуванням розвитку педосфери, як елементу літосферної оболонки Землі, є розущільнення материнської породи з формуванням структурної макропористості ґрунту та розвитком гетерогенності. На прикладі України показано, що геомембранні властивості ґрунтів мають зональну природу і спрямовані на обмеження потужності зони активного енергомасообміну. Концепцію динаміки геомембранних властивостей педосфери, як прояв більш високого ієрархічного рівня геосистемної організації, пропонується використовувати для вирішення суто прикладних питань, таких як оцінювання впливу змін клімату, гумусоутворення і сучасна динаміка родючості ґрунтів, підвищення стійкості і екологічної безпеки використання ґрунтів.*

Ключові слова: *педосфера, ґрунт, термодинамічна система, дисипація, структура порового простору, енергоефективність взаємодії, гомеостаз ґрунту*