A set of physical parameters in the agroecological interaction of agricultural aggregates with soil

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Abstract: An assessment of the current state of land and soil resources has been carried out and the prospects for their long-term use have been predicted. The impact of modern agricultural technologies on the main properties and characteristics of soils has been assessed. The main physicochemical and physical parameters of the soil layer that undergo significant changes during its cultivation and use and affect its quality properties have been identified and analyzed, based on a comprehensive analysis of soil density parameters, it has been established that this parameter is of decisive importance in assessing soil fertility, and that it is subject to significant variations during agricultural processing, a physical-mathematical model based on improving the environmental friendliness of the soil being exploited has been developed and applied. The possibility of using this model to take into account adjustments to soil layer density and to develop technologies for careful, integrated impact on the soil during economic exploitation has been demonstrated. Soil quality properties have been calculated in a mathematical function of environmental friendliness. the necessity of using second-order differential equations in calculations when modeling processes occurring in the soil.

1 Introduction

Currently, the process of exploiting fertile land resources is characterized by a high level of destructive and, in most cases, uncontrolled anthropogenic influence, which gradually provokes irreversible changes in the value characteristics of soils that affect fertility, physical, chemical, and biochemical composition, worsening the outlook for the duration of its safe agricultural use. Roughly one billion hectares of land used in global agriculture have already suffered extreme irreversible degradation, contributed to by erosion, excessive salinization, and other harmful and dangerous technogenic and anthropogenic factors [1]. Due to fierce competitive market mechanisms and the pursuit of maximum productivity and profit, large agro-industrial holdings and agricultural giants rarely consider the global problem associated with the future of humanity in the not-too-distant future: we may lose the land wealth of soil resources that previous generations of people have preserved for us,

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carefully and respectfully cultivating the land and preserving its unique fertile qualities. This truth must be strictly enforced and monitored—humanity must protect, improve, and not subject the natural reserves of fertile soils and other natural resources to destructive exploitation, preserving them and their quality for future generations [2, 3]. This philosophical idea lies at the heart of the basic ecological law reflecting the interrelationship between the three main elements of interaction in the soil-fertility-soil cultivation system.

People must view this task on a global level and solve it on a global scale. This requires strict control over compliance with environmental standards in agricultural technologies. This is easier to achieve now, when agricultural production is becoming globalized around the world and large commercial structures and agro-industrial enterprises are actively working in this sector. Currently, the issue of the quality exploitation and conservation of natural soil resources remains extremely complex and relevant.

As a result of numerous studies, it has now been established that long-term and stable super-resilience has been almost completely lost in natural humus soil systems. For every 10 years of exploitation, the fertile properties of existing soil resources decrease by 0.3%, which represents a catastrophic level of change in global terms. More than half of the particularly fertile black soil lands have irretrievably lost up to 50% of their resource reserves and useful characteristics, which is confirmed by the results of long-term studies. At the same time, important factors that have an irreversible detrimental effect on the state of soil resources in use have become both the violation and incorrect maintenance of agricultural land cultivation and processing technologies, as well as changes in the global climate of our planet associated with the anthropogenic impact of humans on the environment as a whole.

Given the above problem, it is obvious that no industry, including agriculture, can halt its natural development solely for the sake of preserving pristine nature. However, one of the fundamental factors in the technological evolution of the agricultural industry should not be measures to limit the volume and intensity of land use. It is important to develop new technologies for the agricultural sector, guided by the principle of avoiding irreversible soil degradation and refraining from the pursuit of excessive profits in order to preserve the land.

2 Samples and experimental techniques

The main objective of this scientific work is to analyze and select the physical and physicochemical parameters of soil parameters that are subject to critical mechanical stress during technological processes in the agricultural cycle. The main criterion for influence in the study was the assessment of changes in soil fertility. The primary influencing factor was selected as the compression of the soil layer when agricultural machinery passes over it. A physical-mathematical model was developed to achieve this goal. The criteria and content of the model are aimed at assessing the dynamics of processes occurring in the soil under the force pressure of agricultural machinery. The application of the model to conditions of careful comprehensive impact on the soil is considered as a limiting factor. The main research method in this work is physical and mathematical modeling [4]. The modeling involved a quantitative description of soil parameters, taking into account the law of conservation and conversion of energy in the soil environment and the thermodynamic processes occurring in it during cultivation. The model is based on the calculation of the dynamics of physical and physicochemical parameters of the soil with the implementation of the principle of non-destructive environmental impact on the soil. During the modeling process, a detailed analysis of soil compaction was carried out, taking into account the spatial distribution of force vectors from the support mechanisms of the agricultural unit

and the traction device. The effect of mechanical energy absorbed as a result of compression was also taken into account. The relationship between the compressive action of an agricultural machine and changes in the qualitative properties of the cultivated topsoil layer is shown.

3 Results and discussion

A whole range of internal and external parameters influence soil fertility. Among them, the level of gas saturation in the soil is the most significant [5]. The dynamic force exerted by agricultural machinery during soil cultivation primarily and most significantly causes changes in the gas component. This is due to the fluidity of gases and their rapid expulsion from the soil mass under the action of compression. The surface layer of the earth performs a dual function in the process of crop production. On the one hand, it is a condenser and generator of harmful greenhouse gases. According to available data, these gases can have a significant impact on climate change. These changes can be local in scale and affect only certain areas of agricultural fields or regions where agricultural technology is used, or they can have an integral impact on global atmospheric processes. On the other hand, the right gas environment in the soil is the basis for successful plant growth. Let's consider oxygen gas. This gas is the main component of plant nutrition. But it has another important and useful purpose in terms of fertility. Oxygen is a component of the life activity of microorganisms that decompose organic waste produced in the agricultural cycle and process organic fertilizers, creating processes of soil regeneration and enrichment. The critical lower limit of oxygen content for normal plant development is 11%. In addition to oxygen, continuous access to nitrogen gas in the soil layer is necessary. This gas is present in atmospheric air in relative amounts of about 78%. Its content in the soil contributes to the proper development and life of nitrogen-fixing bacteria. Another important gas component of the soil is carbon dioxide, which has a critical upper concentration value in the soil gas environment of 5%. If the barrier values for the content of these gases are violated, the processes of vegetation and plant development are inhibited.

Air capacity and air permeability are used to quantitatively assess the gas composition and gas saturation dynamics of the soil layer. These parameters characterize gas exchange in the soil layer and reflect the normal level of fertility. Soil density and porosity are also important functional parameters that reflect the level of soil fertility. An example of this is the vegetative development of grain crops, where the air content must vary within limits not exceeding 20% of the total porosity of the arable layer. When cultivating porous soils with a regular structure, the gas exchange process occurs at an optimally high rate. This contributes to the effective absorption by the roots of the gases required for plant development. In compacted soils with a disturbed structure or completely unstructured soils, the rate of gas absorption by plants is much lower, which significantly affects the fertility of such substrates.

One of the most significant physical parameters of soil, inextricably linked to gas exchange and absorption, which determines crop yields and the overall fertility of cultivated land, is its density. During the technological application of agricultural machinery, soil density increases on average by up to 20%. Distortion of the soil layer structure is observed to a depth of approximately 0.5 m on average, and in a horizontal projection extending up to 1.0 m on both sides of the path of the processing units. The extent of compaction is influenced by the weight of the equipment and traction device, the number of passes, and the physical parameters of the cultivated soil. The accumulation of deformation of the earth layers is also relevant and is observed in the lower soil layer below the plowing level. It has also been established that soil compaction as a result of cultivation has a tendency to persist for up to 3 years. Figure 1 shows how soil density changes after

agricultural machinery has been used during the main stages of cultivation when growing agricultural crops. The horizontal lines indicate the optimal soil cover density level, which is most favorable for the industrial-scale growth of valuable field crops.

The cultivation of agricultural land inevitably involves the use of soil compacting units and machines. Modern devices of this type are made of heavy iron-based steels with a high specific weight [6, 7]. It should be noted that high-quality structural materials are currently available for the production of agricultural machinery, manufactured using the thermal, baric, and concentration polymorphism properties of this chemical element [8]. An even more promising direction is the use of rare earth metals as alloying elements in steel production [9, 10].

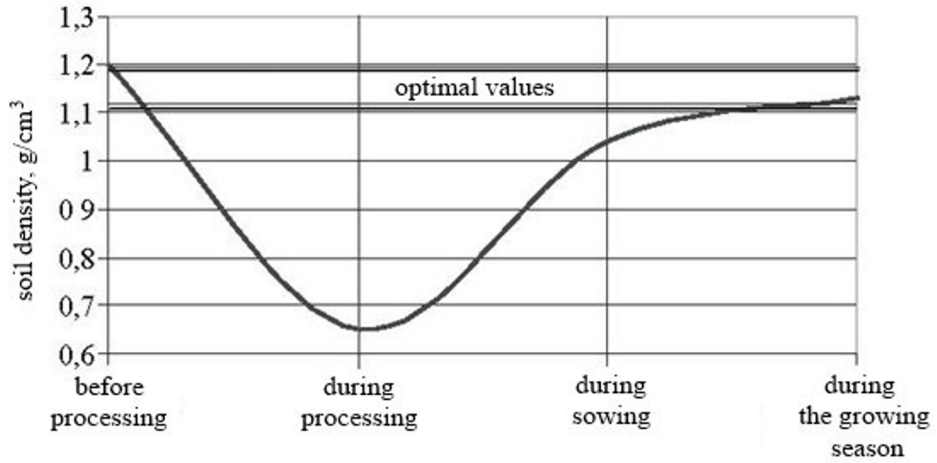

Fig. 1. Soil density dynamics in the agricultural technology cycle

When agricultural machinery passes over the soil, compression occurs at the points of contact between the wheels and other supporting mechanisms, reaching an average pressure of 0.5 MPa. This pressure kills small living organisms that create the structure and fertile component of the soil. Taken together, the impact of such values significantly changes the physical and physicomechanical parameters of the soil layer, reducing crop yields by up to 50% and increasing the cost of agricultural production due to higher energy and material costs. The use of agricultural machinery destroys the top layer of soil, which subsequently causes erosion. Modern agricultural processing units and traction devices have high productivity, which is dictated by the level of technological progress. This characteristic of modular processing equipment is often associated with an increase in its weight. The use of equipment with a combination of various heavy attachments leads to an increase in the total load on the soil during its cultivation. The increase in soil density and the degradation of the fertile layer due to its abrasion have accelerated significantly as a result of the overall increase in the weight of high-performance agricultural equipment. Large tractors with mounted equipment contribute to an increase in soil hardness by up to 5 times, necessitating an increase in the force exerted by the working parts of this equipment during subsequent cultivation of the cultivated areas. External compression disrupts soil porosity. As a result of reduced water and air availability in compacted soil, crop yields decline.

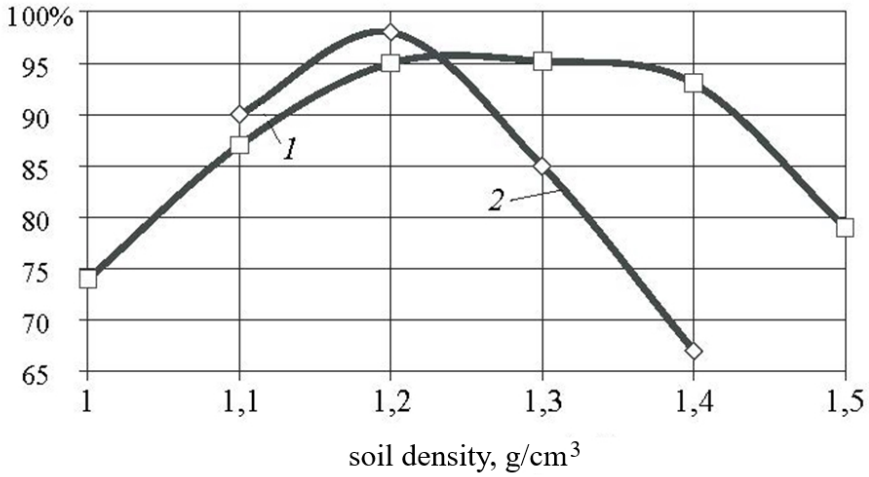

Fig. 2. Dependence of relative yield on soil density: 1 – alfalfa; 2 – beet

Figure 2 shows the median result of numerous studies examining the relationship between the relative yield of well-known and common agricultural crops - alfalfa and sugar beets - and the density function of the soil layer.

To improve soil fertility, increased doses of mineral fertilizers are used. This method results in acidification and a decrease in humus levels, which affects the fertility and quality of the soil cover. A scientific approach to proper agricultural land management is a close connection between the physics of the cultivation process and the agronomic component, which forms the basis of an agroecological approach to agricultural crop production.

The most rational way to describe the impact of agricultural machinery on the soil is to develop a physical model that takes into account the interrelationships between dynamic and energy parameters in various physical and physicochemical processes in soils. The quality of the physical and mathematical apparatus forms the basis for evaluating the created model of the technological process. To simulate the mechanical change in soil structure during compaction caused by the operation of mobile agricultural machinery, a model that takes into account the effect of energy absorbed by the soil is suitable. The model is based on the use of the fundamental law of conservation and conversion of energy in the soil environment and its application to the thermodynamic processes occurring in it during processing.

Soil porosity is a physical property important for fertility and normal soil management. Optimal pore sizes range from 100 to 300 μm. These pore sizes facilitate the efficient transport of moisture and various gases by plant roots. The passage of agricultural equipment support systems across the soil surface reduces pore sizes to an average of 10 μm. Compression to these values alters the thermodynamic properties of soils (P, V, T) and impedes the exchange of liquid and gas solutions by a factor of 2 - 4, significantly altering the temperature regime, which leads to a decrease in the productivity of agricultural technologies. To assess the effect of soil density on the rate of its degradation and destruction, a function $f(e)$ can be proposed - optimally referred to as the ecological density function or the ecological function. This function must correlate and interrelate with the maximum and minimum soil density values $_{min}$ and $_{max}$. We will use the following expression for this relationship:

$$f(e) = \frac{(- \quad _{min})}{(\quad _{max} - \quad _{min})}$$

The values of the ecology function are normalized and range from $0 < f(e) < 1$.

When creating a physical model, it should be taken into account that excessively loose soil dries rapidly due to convective diffusion and also exhibits intense humus mineralization. The set of parameters for assessing the mechanical impact of the agricultural implement's working element on the soil should include dynamic characteristics that account for shear force and efficiency, friction of the implement's surface against plant roots and the soil (both its working and non-working surfaces), the impact forces of displaced soil elements, and the diverse kinematics of the mechanical process. The forces describing soil cutting resistance differ from the cutting forces of plant roots due to differences in their physical and mechanical manifestations. Incorporating an element of interaction with plant roots into the model structure requires an algorithm capable of accounting for the chaotic growth and distribution of roots. To accurately analyze the dynamics of the interaction process, it is necessary to determine and mathematically describe the law of motion of the reference points of the agricultural implement's working elements and the traction mechanism. A high-quality physical and mathematical model requires consideration of the non-stationary and random distribution of the reaction force. A distinctive feature of the environmentally effective model of soil interaction with the working parts of the agricultural machinery used is its binary nature. The model implements the relationship between fertility indicators and the energy characteristics of ongoing biological processes. Fertility is characterized by the level of humus in the soil. The second important link in the model is the determination of the nature of changes in the thermodynamic parameters of the soil layer, which are determined by the specific volume of pores contained in it in the dynamics of pressure and temperature of the fertile layer of cultivated soil. The criteria for a correct model should also include a parameter that reflects the amount of daily energy intake associated with the cyclical nature of daily processes, which changes under the influence of technology. Soil compaction is accompanied by a decrease in thermal conductivity. Faster heat energy transfer leads to changes in daily temperature differences. Obtaining a structured, complete model of soil dynamics and fertility is only possible with the correct consideration of the factors and adjustments indicated. These factors must have a complex interrelationship that takes into account mechanical, thermodynamic, and cyclical processes, with consideration for the ecological priority in the soil-agricultural machinery system. Subsequent detailed analysis of the proposed model will provide the basis for a new model for the restoration of degraded land resources.

Existing and naturally occurring soil biosystems form a multicomponent complex of internal systemic relationships and possess the capacity for self – organization under constant external influences. Such structures are complex nonlinear dynamic systems capable of regeneration in the presence of necessary favorable external influences, which determine their capacity for stability and self-organization. When modeling soil processes, attention is drawn to states of relative stability-quasi-equilibrium states. Their quality is the ability to direct the course of self-organization for effective fertility management, although dissipative factors may also influence cyclic processes in the soil layer. Over the time interval of a technological process for agricultural land cultivation, the proposed physical model describing the interaction of an agricultural unit with the soil can be represented as a model with multiple influencing factors that overlap during the description and require consideration through the principle of superposition. It should be noted that the boundary states in the modeling should relate to the area of environmental risk for the cultivated soil associated with probabilistic uncontrolled destruction under the action of a mobile agricultural unit. First-order differential equations are mainly used in modeling soil

processes. In such models, the rate of biological processes is represented by simple differentials. To describe the dynamics of the ecological components of processes, second-order differential equations were used in this work. The application of this mathematical apparatus makes it possible to model the impact of technological machines on the dynamics of normal basic natural processes in the upper layers of the soil affected by agricultural machinery. A variant of the obtained equation within the framework of the proposed model is an equation of the form:

$$\frac{d^2m}{dt^2} = f(n,k)\left(\sum F_n + \sum F_k\right)m,$$

where $\frac{d^2m}{dt^2}$ – is the component of the equation responsible for the change in the rate of humunization in the soil layer, F_n – is a function that takes into account the degree of impact of the processing organs of the agricultural unit and the traction device, F_k – is a function that takes into account the presence and effect of external factors, including the effects of global warming, m – is the humus mass, and $f(n,k)$ – is the response function of the soil biosystem to man-made and natural impacts of various kinds.

4 Conclusions

Based on publicly available information, approximately 90% of arable land in the domestic land fund exhibits negative fertility dynamics, indicating ongoing degradation of these lands. A key aspect of analyzing the performance of modern agricultural machinery is accounting for their impact on the soil layer, which causes significant deviations in the soil bio-inert system from equilibrium. Critical changes occurring in fertile soil layers, characterized by a significant adjustment of normal fertility parameters, will lead to the complete destruction of the soil cover without anthropogenic corrective intervention. Critical conditions imply uncertainty in the parameters that characterize them, which take on extreme values in such conditions. In a mathematical approximation, it becomes impossible to use estimates of the thermodynamic properties of soil processes in the modeling process, where there are no limits on the dynamics of masses and energies. Calculation using linear systems of mathematical equations of the humus mass distribution gradient in a given direction in space in the fertile soil layer implies taking into account two interrelated variables. One of them should describe the features of the technology used to cultivate planting areas. The other variable is related to internal, relatively slow processes of microorganism distribution in a soil layer of a certain density and moisture content. The analysis of the rate of microorganism reproduction and penetration conducted in the studies shows that within 3 hours, microorganisms are able to recover in a soil layer 1 cm thick. This parameter is strongly dependent on the current thermodynamic parameters of the soil and the processes occurring under these conditions. For example, a decrease in daily temperature in central Russia leads to a decrease in the decomposition rate of plant residues and other organic matter in the soil by approximately half for every 10°C change in temperature during the spring-fall period.

Multiple sets of state parameters, the complex nature of the relationships between them and the factors affecting the soil ecosystem, and the need to take into account the integrity of the natural soil system determine its state and conditions for normal functioning. In the process of anthropogenic intervention in agricultural production, it is necessary to carefully analyze and take into account the changes taking place in it, otherwise irreversible disturbances begin to occur in the soil system, leading to its destruction. When using crop cultivation technologies, it is important to maintain a balance in the soil of moisture, air, small animals, and microorganisms that create favorable conditions for the soil layer itself.

The promising new-generation crop production systems being introduced must meet these conditions, otherwise soil resources will be depleted within the next century. Promising technologies for plowing, cultivation, and fertilization of land should provide for the maximum possible adaptation of technological processes to the natural parameters of the environment. This will preserve the physical and ecological properties of the soil cover for long-term and safe use in crop rotations. The application of ecological principles in modern agricultural production technologies will make it possible to preserve the planet's invaluable soil resources, maintaining land productivity and soil fertility, as well as ecological stability.

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