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IMPROVING SOIL HEALTH AS A DRIVER OF AGRICULTURAL SUSTAINABILITY AND CLIMATE RESILIENCE

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The article explores the role of improving soil health as a key factor in ensuring sustainable agricultural development and increasing its resilience to climate change. The relevance of the topic is due to the intensification of global climate transformations, the degradation of soil resources and the growth of risks to food security. It has been established that traditional models of agricultural production do not provide the necessary level of adaptability of agroecosystems, which makes the search for new approaches to natural resource management relevant.

The paper summarizes modern scientific approaches to understanding the concept of "soil health" as an integral characteristic of its ability to perform ecosystem functions, in particular, ensuring bioproductivity, regulating the water regime, maintaining biodiversity and accumulating organic carbon. Particular attention is paid to the role of soils in the global carbon cycle, where they act as one of the largest carbon reservoirs and an important tool for mitigating climate change.

It is substantiated that the key factor in the formation of soil carbon potential is the activity of microorganisms that ensure the transformation of organic matter and regulate biogeochemical cycles. It is shown that climate change affects microbiological activity, which, in turn, determines the dynamics of carbon flows in the soil-atmosphere system. It is proven that the implementation of sustainable agricultural practices, such as minimum tillage, the use of cover crops, agroforestry and crop rotation optimization, contributes to an increase in the content of organic carbon, improving soil structure and its water-holding capacity.

The impact of irrational land use, degradation processes and imperfect management systems on the reduction of soil fertility and their ecological functions is considered. Approaches to improving soil quality based on the principles of climate-oriented and circular agriculture are proposed, including crop diversification, organic matter restoration, the implementation of effective irrigation systems and monitoring.

It is concluded that improving soil health is a systemic factor in ensuring the sustainability of agricultural systems and an important tool for adapting to climate change, which requires integration into state policy and agricultural sector management practices.

***Key words**: soil health, climate change, soil resource degradation, food security, ecosystem functions, bioproductivity, land use.*

Омельяненко Віталій, Корнус Анатолій. Покращення здоров'я ґрунту як рушійна сила сталості сільськогосподарської діяльності та кліматичної стійкості

У статті досліджується роль покращення здоров'я ґрунтів як ключового чинника забезпечення сталого розвитку сільського господарства та підвищення його резильєнтності до кліматичних змін. Актуальність теми зумовлена посиленням глобальних кліматичних трансформацій, деградацією ґрунтових ресурсів і зростанням ризиків для продовольчої безпеки. Встановлено, що традиційні моделі агровиробництва не забезпечують необхідного рівня адаптивності агроекосистем, що актуалізує пошук нових підходів до управління природними ресурсами.

У роботі узагальнено сучасні наукові підходи до розуміння концепції «здоров'я ґрунту» як інтегральної характеристики його здатності виконувати екосистемні функції, зокрема забезпечення біопродуктивності, регулювання водного режиму, підтримки біорізноманіття та акумулювання органічного вуглецю. Особливу увагу приділено ролі ґрунтів у глобальному вуглецевому циклі, де вони виступають одним із найбільших резервуарів вуглецю та важливим інструментом пом'якшення кліматичних змін.

Обґрунтовано, що ключовим фактором формування вуглецевого потенціалу ґрунтів є діяльність мікроорганізмів, які забезпечують трансформацію органічної речовини та регулюють біогеохімічні цикли. Показано, що кліматичні зміни впливають *на мікробіологічну активність, що, у свою чергу, визначає динаміку вуглецевих потоків у системі «ґрунт–атмосфера». Доведено, що впровадження сталих агропрактик, таких як мінімальний обробіток ґрунту, використання покривних культур, агролісомеліорація та оптимізація сівозмін, сприяє підвищенню вмісту органічного вуглецю, покращенню структури ґрунту та його водоутримуючої здатності.*

Розглянуто вплив нераціонального землекористування, деградаційних процесів і недосконалих систем управління на зниження родючості ґрунтів і їх екологічних функцій. Запропоновано підходи до підвищення якості ґрунтів на основі принципів кліматично орієнтованого та циркулярного сільського господарства, включаючи диверсифікацію культур, відновлення органічної речовини, впровадження ефективних систем зрошення та моніторингу.

Зроблено висновок, що покращення здоров'я ґрунтів є системоутворюючим чинником забезпечення сталості аграрних систем і важливим інструментом адаптації до кліматичних змін, що потребує інтеграції у державну політику та практики управління аграрним сектором.

Ключові слова: *здоров'я ґрунтів, кліматичні зміни, деградація ґрунтових ресурсів, продовольча безпека, екосистемні функції, біопродуктивність, землекористування.*

Introduction. The modern development of the agricultural sector takes place in conditions of increasing global climate change, degradation of natural resources and growing food challenges. Changes in temperature regimes, increased frequency of extreme weather events, disruption of water balance and erosion processes significantly affect agricultural productivity, especially in regions with high anthropogenic load. In these conditions, traditional approaches to agricultural production are not effective enough to ensure long-term sustainability and adaptability of agroecosystems.

One of the key, but often underestimated factors in ensuring the sustainability of agricultural production is the condition of soils. Intensive land use, excessive chemicalization, crop rotation violations and irrational management of agricultural landscapes have led to a decrease in soil fertility, loss of organic matter, a decrease in biodiversity and a deterioration of their physicochemical properties. This, in turn, limits the ability of soils to perform ecosystem functions, in particular, regulating the water regime, accumulating carbon and ensuring stable yields.

The problem becomes particularly relevant in the context of the need to increase the resilience of agricultural systems to climate change. Healthy soils are considered the basis of the adaptive potential of the agricultural sector, as they are able to increase resistance to droughts, reduce erosion risks, improve water retention capacity and contribute to reducing greenhouse gas emissions. At the same time, the issue of integrating approaches to improving soil conditions into the strategy for sustainable development of the agricultural sector and climate policy remains insufficiently developed both in scientific and managerial dimensions.

Thus, a scientific and practical problem arises of substantiating the role of improving soil conditions as a system-forming factor in ensuring the sustainability of agriculture and increasing its resilience to climate change. The need for a comprehensive study of this relationship, as well as the definition of effective mechanisms for managing soil resources, determines the relevance of this scientific article.

Literature review. The issue of improving soil health as a basis for sustainable agriculture and climate resilience is actively researched in modern scientific literature. The conceptual foundations of the concept of "soil health" and its functional significance are revealed in the work (Lehmann et al., 2020), which emphasizes that healthy soil is a dynamic system capable of supporting biological productivity, ensuring environmental quality and contributing to the stability of ecosystems.

The important role of soils in global climate processes is substantiated in studies (Lal, 2004) and (FAO, 2015), which prove that soils are one of the largest carbon reservoirs, and their rational use can significantly reduce the concentration of greenhouse gases in the atmosphere. In particular, (Lal, 2004) emphasizes the potential of carbon sequestration as a key mechanism for simultaneously ensuring food security and mitigating climate change.

Further development of this idea is presented in the works (Minasny et al., 2017) and (Kane & Solutions, 2015), which analyze the potential for soil organic carbon accumulation through the implementation of sustainable agricultural practices. In particular, the "4 per 1000" initiative (Minasny et al., 2017) demonstrates that even a small annual increase in soil organic carbon can have a significant global climate effect.

In the context of agricultural adaptation to climate change, a systematic review (El Chami et al., 2020) is important, which summarizes sustainable agricultural practices such as minimum tillage, use of cover crops and agroforestry.

Empirical studies of organic carbon in agrosystems also confirm the importance of soil management. In particular, a meta-analysis (Emde et al., 2021) demonstrates that good irrigation and soil management practices can contribute to the accumulation of organic matter, which directly affects the productivity and resilience of agroecosystems.

Recent research also focuses on soil microbial processes. (Domeignoz-Horta et al., 2023) demonstrated that substrate availability is a key factor determining the response of microbial communities to temperature increases, which is important for predicting changes in the carbon cycle under global warming.

Also significant is a study (Radulov & Berbecea, 2023), which directly addresses the role of soil health in mitigating climate change.

In the broader context of sustainable development, the role of soils as an element of ecosystem services is considered in the work (Telo da Gama, 2023), which emphasizes their importance for maintaining biodiversity, regulating climate and ensuring food security. The author emphasizes the need to integrate soil policy into overall sustainable development strategies.

The general state of soil and land resources and the challenges of their degradation are summarized in the report (FAO, 2021), which emphasizes the global nature of the problem of soil depletion and the need to transition to sustainable models of natural resource management.

Analysis of scientific sources indicates that soil health is a key systemic factor in ensuring the sustainability of agriculture and increasing its resilience to climate change. At the same time, there is a need for further research into the mechanisms for integrating soil conservation practices into agricultural development and climate adaptation policies.

The purpose of this study is to comprehensively substantiate the role of improving soil health as a key factor in ensuring sustainable agricultural development and increasing its resilience to climate change, as well as to identify effective approaches and mechanisms for managing soil resources that contribute to the restoration of their ecosystem functions, in particular the accumulation of organic carbon, regulation of the water regime, and maintenance of the bioproductivity of agroecosystems.

Results. Climate change can affect many processes in the Earth's biosphere, including the cycles of nutrients necessary for living things. Such cycles (primarily the carbon cycle) are highly dependent on the activity of soil microbes.

The biosphere is the global ecosystem of the Earth and consists of many different components closely connected by common flows of matter and energy. Of particular importance for all living things are the cycles of biogenic, which is accompanied by their chemical and physical transformations.

When talking about carbon, it's important to remember the huge role soil plays in the carbon cycle (Fig. 1). Soil cover is one of the key reservoirs of carbon, which constantly exchanges this element with its other storages – living organisms, the atmosphere, and so on.

The dynamics of carbon in the soil is determined by the microorganisms living in it, which play the role of "catalysts" of geochemical cycles. These tiny cells work tirelessly to convert vast amounts of one compound into another. It is natural to expect that under conditions of climate change, on the one hand, the microscopic inhabitants of the soil should be activated, and on the other, carbon flows should be redistributed between its key storages. The same can be said about other so-called biogenic elements – for example, nitrogen. However, there has not yet been a detailed understanding of such connections.

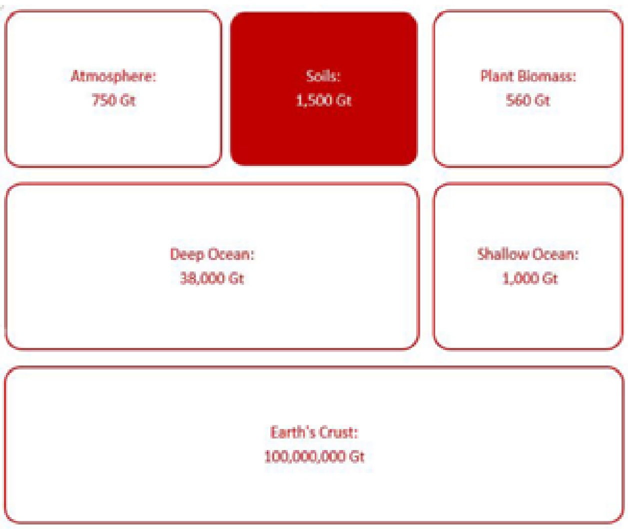

Fig. 1. Earth's carbon reservoirs, gigatons (McDowell, 2019)

The carbon cycle (Fig. 2) deserves special attention, because this element underlies all living things, and at the same time important greenhouse gases: carbon dioxide and methane.

Soils are one of the most important carbon sinks. They capture and store more carbon than the entire atmosphere and the total plant environment combined (Lal, 2004).

The process of carbon absorption is a complex combination of biological, chemical and physical factors, but its potential in soils to significantly reduce the level of CO_2 in the atmosphere cannot be overestimated (Telo da Gama, 2023). Different types of soil store carbon differently. These features are determined by such factors as mineral composition, texture, land use methods, microbial composition of soils (Lal, 2015).

It is worth citing the following fact: an increase in global carbon stocks in soils by only 0.4% per year can offset the annual increase in CO_2 emissions. This figure makes it extremely important to use the potential of soil management as part of a global climate change mitigation strategy (Minasn, et al, 2017).

Land use practices such as cover crops, conservation tillage, crop rotation, and organic incorporation not only improve soil carbon storage capacity, but also contribute to overall soil health by promoting microbial diversity and organic matter stabilization (Emde, 2021). Research is currently underway to optimize these methods to maximize carbon storage while maintaining long-term food security (Kane & Solutions LLC, 2015).

The basic mechanism of carbon transfer into the soil is photosynthesis and subsequent storage in the roots of plants, which are decomposed into soil organic matter. Plants accumulate CO2 from the atmosphere and accumulate it in biomass, the decomposing residues form carbon in the soil (Fig. 3).

The carbon content in the soil is determined by a wide range of factors (climate, biotic properties of plants and microbes, physical and chemical properties of the soil, which determine its carbon content). From the perspective of the biosphere, soil organic carbon forms one of the largest components of the terrestrial carbon stock for ecosystems and the global carbon cycle (Shibabaw, Rappe, & Gärdenäs, 2023). From the point of view of this study, the thesis that the amount of soil organic carbon is formed as a result of complex processes of natural (primary) and anthropogenic nature is important, with the latter prevailing in modern conditions (Wan et al, 2021).

The primary sources of organic carbon are biogenic (emissions of volatile organic compounds by vegetation, biological particles – pollen, plant residues, soil, dust, bacteria and viruses, forest fires, volcanic emissions, plankton activity), anthropogenic (combustion and production of fossil fuels and ethanol, biomass burning,

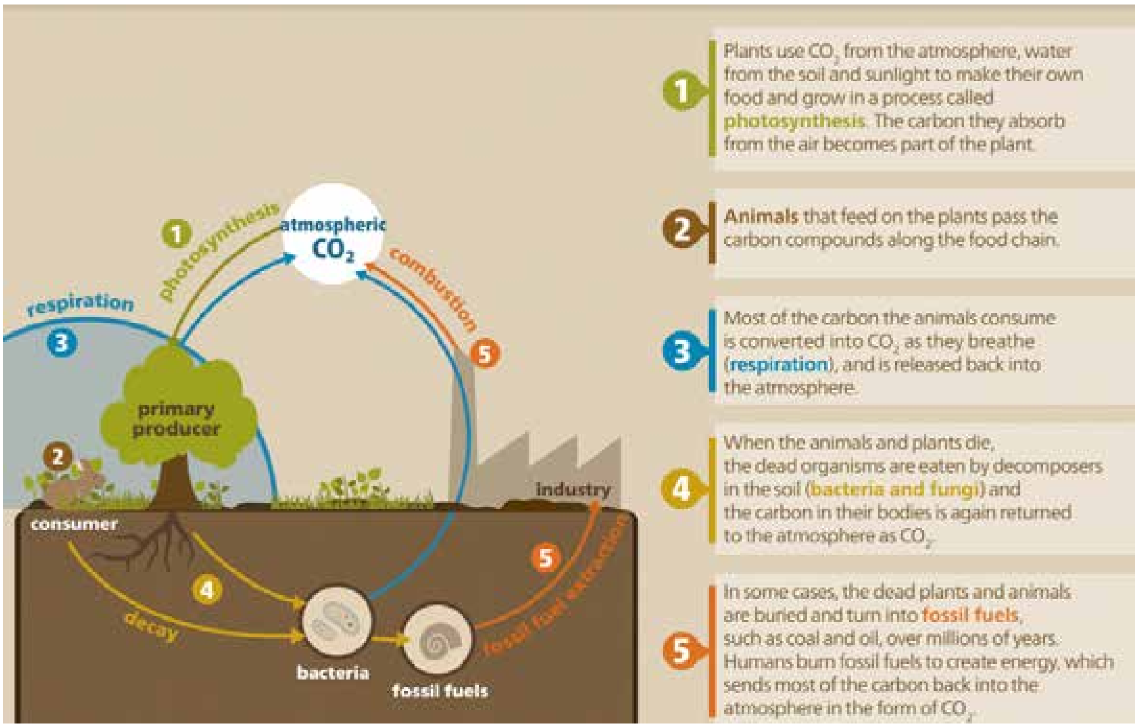

Fig. 2. Soils and Carbon Cycle (FAO, 2015)

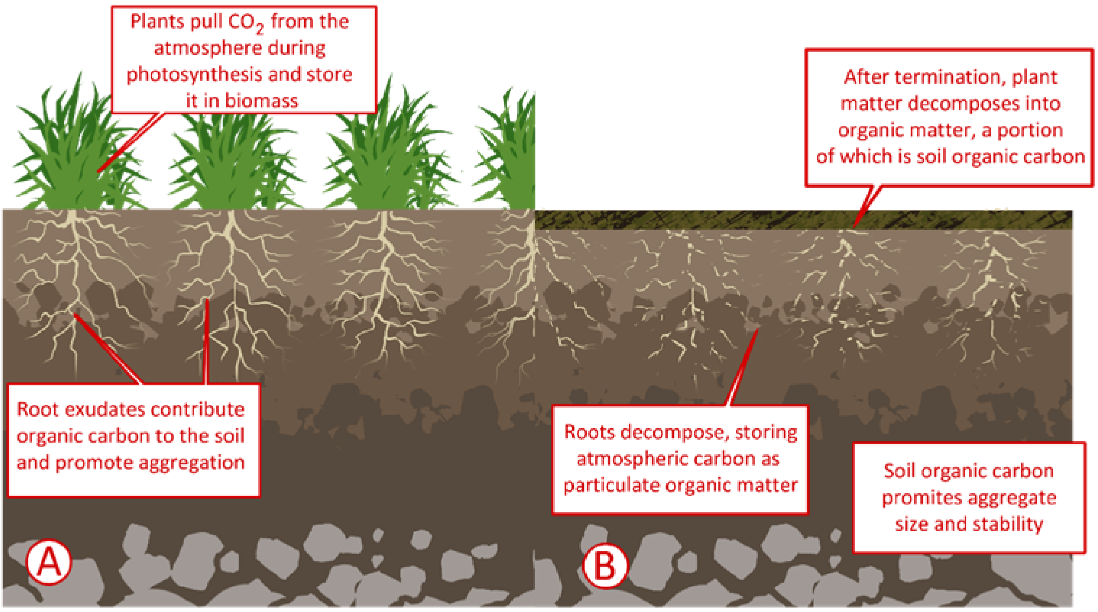

Fig. 3. Diagram of how plants sequester carbon A) before, and B) after termination (McDowell, 2019)

household heating and cooking, solvent use), emissions from agriculture (e.g. pesticides) and natural gas exploration are released into the atmosphere as gases and particulates. Soil gases are in a dynamic exchange with the atmosphere, and its lack results in a deterioration of the environment for microbiological life, generation and adsorption of nutrients and their transformation into an assimilable form. After exchange with the atmosphere, the soil receives oxygen and in the course of its ,consumption removes it due to the higher concentration in the soil. The release of CO_2 from the soil can be considered as an indicator of microbial activity and soil fertility. Thus, fertile soils emit more than 60 mg of CO_2/kg/day, and infertile soils emit less than 30 mg of CO_2/kg/day (Crista et al, 2020).

Soil carbon content is directly related to the activities of microorganisms, which account for more than 95% of soil biomass and play a fundamental role as primary producers and decomposers in soil carbon cycling and sequestration (Wang et al., 2023). Most soil microorganisms are heterotrophs that use organic matter as energy for growth and reproduction (Liao et al., 2023). At the same time, soil microorganisms spend energy on both constructive and destructive processes. Due to the heterotrophic destruction of organic matter, CO2 can be emitted in quantities that often exceed anthropogenic inputs. It is known that soil microbiota is distributed unevenly throughout the depth of soil horizons; the maximum number and diversity of soil microbiota is observed in the upper 0-10 cm layer of soil. Its typical representatives are bacteria of the genera Acidobacteria, Actinobacteria, Bacteroidetes, Proteobacteria, Verrucomicrobia and micromycetes of the genera Ascomycota, Basidiomycota, Chytridiomycota, Rozellomycota, Unassigned (Xu et al., 2023). In addition, soil microbiota represents another form of carbon storage in the soil. To form conclusions about the distribution of carbon in different soil layers, it is important to evaluate different pools.

Soils as an important buffer (regulator) of the climate change process are still a source of carbon dioxide emissions, but conservation agriculture practices can help stop and, in some cases, reverse the loss of soil organic carbon (Fig. 4).

To untangle the complex relationships between soil microbes, their environment and global climate change, Domeignoz-Horta et al (2023) in the laboratory monitored changes in the physiology of microbes obtained from a range of soils at two experimental sites at Harvard University. Previously, they were observed for a long time during studies on changes in soil temperature that lasted 13 and 28 years. Microbes for analysis were selected at different times of the year. Next, they were cultivated under different temperatures (from four to 30 degrees) to trace the connection of this factor with the metabolism of microorganisms. Their growth rate, respiration, carbon utilization efficiency, and extracellular enzyme activity were assessed. Changes in the chemical composition of organic components of the surrounding soil were also analyzed. The authors of the study were able to find out that rising temperatures suppress the release of carbon dioxide by soil microbes, but only in summer. This is due to their fasting during the warm season. In other seasons, the activity of soil microflora remains generally unchanged.

Excessive load on the soil leads to progressive degradation of the soil cover and the development of water and wind erosion processes, which reduces the quality and, therefore, productivity of the soil by 20%, 40% and 60–80%, respectively, with weak, medium and strong erosion (Ursu, 2011).

"Soil health" or SoilHealth is a new term introduced into science and world agricultural practice more than 20 years ago, which made it possible to understand which direction to move in crop production, gave impetus to the development of new biologized technologies, and brought countries implementing soil health methods into leading exporters food.

Soil health is defined as the ability of soil to function as a vital ecosystem that supports plant life, animal life and humanity, and links agricultural and soil science to policy, stakeholder needs and sustainable supply chain management. In retrospect, soil assessment was focused primarily on crop production, but in today's context, soil health also includes aspects of water quality, human health, and climate change. A leading modern concept is the consideration of ecosystem services provided by soils, indicators for assessing soil functionality, and their integration into soil health indices (Lehmann et al, 2020).

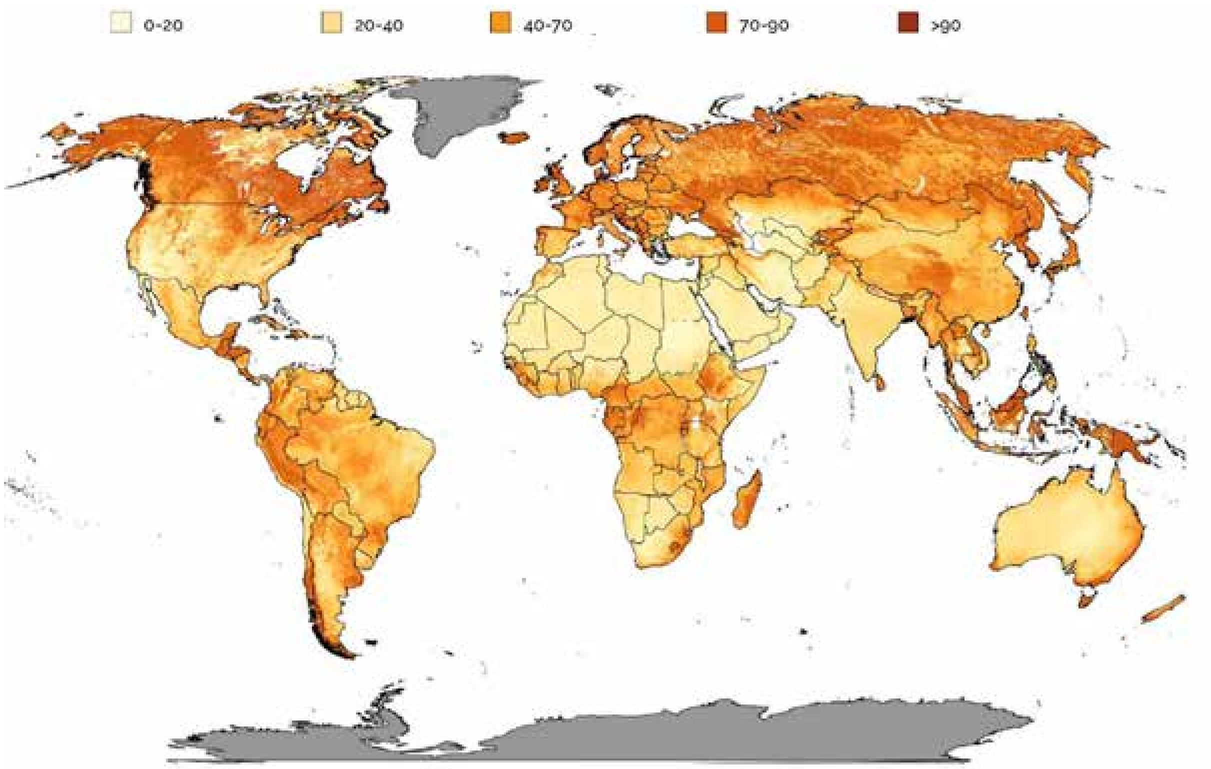

Fig. 4. Global soil organic carbon stocks, tonnes/ha, 2019 (FAO, 2021)

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Case. New crops to improve soil structure

Experts from the Institute of Horticulture (HBLFA, 2019) located in Tyrol suggest experimenting with new crops that will have a positive effect on the soil. For example, leguminous plants are important in organic agriculture, as they participate in the distribution of nutrients in crop rotation, improve soil structure. Subsequently, they are used for fattening animals.

Climate change will increase dry periods in the summer, so some researchers think it's worth growing new crops: lentils or sweet potatoes. Since the main phase of growth and development of many agricultural crops occurs from spring to autumn, many plant species are vulnerable to extreme heat. Due to strong yield fluctuations in recent years, especially among summer leguminous crops, scientists have turned their attention to winter crops.

Winter legumes of various origins are tested for suitability and effectiveness in the foothills of the Alps. Yes, they want to grow sustainable plants that can close the protein gap in organic agriculture. In addition, such plants make a significant contribution to nitrogen fixation in crop rotation.

Scientists are currently testing special crops, including lentils and beans. They provide farmers with additional sources of income and biodiversity for growing crops. For example, lentils are grown in warmer climates with less rainfall. The change in climatic conditions not only significantly changes the range of cultivated species from summer to winter, but also allows the cultivation of new species as a priority. In addition to lentils and beans, these include tropical crops: sweet potatoes, peanuts, and watermelons.

The United Farmers' Association of Germany (Verband der Landwirtschaftskammern, 2019) has proposed strategies for soil adaptation, focusing on factors of climatic influence:

– preparation of biologically active, mobile, upper layer of soil with sufficient connection with the lower layer of soil. Tillage (mulching or direct seeding) can help protect against erosion and build water-retaining humus. Integrating improved soil structure during crop rotation improves soil porosity and promotes rooting.

– during crop rotation, it is worth taking into account the types of rod root systems that have the property of penetrating into denser layers of the soil (for example, alternating with root crops). This affects the formation of pores, which activates the activity of earthworms, which loosen the soil and create favorable conditions for the following crops.

– avoid soil compaction using the appropriate method of driving machinery and cultivation.

– it is important to investigate the approximate value of humus content in arable soils. In particular, with the help of monitoring programs to assess the impact of various measures on humus dynamics. The availability of such information is important in order to understand how climate change or other factors will affect soil fertility and to take them into account in adaptation measures.

– field design focused on soil conservation. Prevention of the formation of water accumulation on unsown areas in view of the peculiarities of local conditions with the help of functional drainage and greening of areas where crops are not grown. The division of fields, protective and buffer strips, green strips, etc., also contribute to the reduction of erosion.

In conditions of rapid climate change, agricultural producers should practice climate farming. And it is a holistic system that identifies the risks associated with climate change and the best practices for solving these problems. Let's consider two tactics in detail. The first is water conservation. Climate agriculture promotes the development of a number of water conservation practices, such as planting "buffer" trees and shrubs along rivers and streams to prevent soil erosion. The second is soil conservation. Practices such as contour planting or no-till reduce erosion from wind or heavy rains or floods.

Seidu (2016) notes the importance of climate-smart agriculture (CSA), which has the potential to achieve the goals of both food security and climate change prevention, particularly by reducing and removing greenhouse gases when possible.

Based on the analysis of world experience, we can formulate the following recommendations for improving soil quality:

1. Diversification of crop production taking into account the modern agro-climatic zoning of territories.
2. Selection of drought-resistant varieties and hybrids of agricultural crops with high productivity.
3. Increasing the diversity of crops to strengthen the resistance of the agroecosystem to external stresses.
4. Expansion of sown areas for types and varieties of agricultural crops with a short growing season, which will make it possible to obtain two or three harvests of individual crops.
5. Implementation and restoration of effective irrigation systems (in particular, drip irrigation).
6. Restoration and creation of new field protection forest strips (agroforestry).
7. Shifting the sowing dates of spring crops to earlier dates, winter crops to later dates, which will ensure effective use of soil moisture reserves by crops.
8. Implementation of disease and pest monitoring systems.

The problem of greenhouse gases and the release of geological deposits of carbon is usually associated with technogenic factors, but is not always associated with the balance of its consumption and accumulation in biological systems and resources, apparently because this balance is determined by daily human activities. In particular, it is known that agriculture is associated with significant losses of carbon deposits in soils, and livestock farming is one of the main sources of greenhouse gas emissions, primarily methane.

The first statement is certainly true and is easily confirmed in our region, especially in Ukraine, where humus reserves are depleted, quickly approaching critical values. It is also enough to recall the role of large herbivores in the history of humus formation, as well as the fact that any agricultural crop (except alfalfa and clover, necessary for stable livestock farming) removes more organic matter from the soil than it creates, and the fact that carbon is deposited in the soil primarily in the composition of substances containing nitrogen. This means that without some level of livestock production it is difficult to sequester carbon in the soil.

Unsustainable farming practices occur when:

– on the one hand, extremely weak application of mineral fertilizers to arable lands contributes to the release of carbon due to the mineralization of humus, especially against the background of the non-use of siderites;

– on the other hand, the application of mineral fertilizers (due to geological reserves) is also associated with energy costs, mainly the combustion of hydrocarbons;

– regionally, the most important factor is the lack of scientifically based crop rotations that include perennial legumes on 15-25% of the area.

– It should be noted that soil quality is also related to other aspects of the functioning of the agricultural industry. Let's look at the example of unsustainable livestock farming:

– grazing with heavily overloaded pastures creates a negative balance of carbon fixation (together with nitrogen) and its removal, thereby worsening the protective qualities of the grass cover; overloaded grazing is also energy inefficient and provokes additional consumption of organic carbon and destruction of vegetation cover;

– the almost complete absence of stabling for cattle, which is the direct (although not the main) cause of improper crop rotations and a shortage of organic fertilizers;

– the "corn basis" of poultry farming, which makes a serious contribution to uncompensated losses of soil carbon and fertility;

– the grain basis of pig farming, on the one hand, and the characteristic lack of conversion of its waste into organic fertilizers, on the other, turning the industry into a source of greenhouse gases;

– illegal and energy wasteful burning of straw, mainly wheat, instead of effectively using it as fertilizer, for soil mulching or biofuel.

From these problems, we see a number of solutions, which include the application of the principles of the circular economy in the industry to improve soil quality.

Another factor of soil quality in the context of climate change is dual in nature and is associated with the unstable state of reclamation (mainly drainage) systems and associated irrigated agriculture. The observed warming accelerates negative processes due to the poor use of floodplain soils, which also leads to the predominance of organic mineralization processes. Against the backdrop of degradation of these systems, the productivity of crop production is reduced and in this context, the difference between highly productive, quickly fixing carbon floodplain natural ecosystems and agricultural ecosystems is increasing.

Ineffective forest management reduces the fixation of carbon in soils and its deposits in the form of dead wood, both due to the logging age reaching much earlier than the climax in natural forests, and due to the simplified composition and structure of forest stands, as well as the use of wood residues, as a rule, for inefficiently burned fuel; at the same time, it is the harvesting of commercial timber that retains fixed carbon for a long time.

Today we already have a technology for correcting microcenoses that has been proven for different soil and climatic conditions to restore soil health. One of the most important stages of this technology is working with crop residues. This agricultural technique will bring a satisfactory result if, when processing straw before embedding it into the soil, you operate not with individual strains (bacteria or fungi, such as Trichoderma), but with a whole complex of active microorganisms that can "awaken" and mobilize those that are dormant or preserved in the soil in dwarf forms natural microorganisms that restore active soil biomass.

So the term "soil health" is viewed as an indicator that quantifies the soil's ability to perform the following functions: soil water retention, erosion resistance, carbon sequestration, microbiota storage, plant resistance to disease, and provision of plant nutrients. Typically, the operation of each part of the system (biological, chemical and physical) is considered to understand their functioning.

Conclusions. The study has found that soil health is a key system-forming factor in ensuring sustainable agricultural development and increasing its resilience to climate change. It has been proven that soils perform critically important ecosystem functions, in particular, accumulating organic carbon, regulating the water regime, supporting biodiversity, and ensuring stable productivity of agroecosystems. In the context of global warming, it is the ability of soils to sequester carbon that is gaining strategic importance as a tool for mitigating climate change.

Analysis of modern research and practices shows that soil degradation caused by intensive land use, crop rotation violations, and irrational use of fertilizers and agricultural technologies significantly reduces their functional potential. A special role in the transformation of soil processes is played by the microbiota, which determines the dynamics of the carbon cycle and sensitively responds to climate change. At the same time, it has been established that effective management of organic matter and support of biological activity of soils can increase their adaptive potential.

It has been substantiated that the implementation of soil-conserving and climate-oriented practices, such as minimum tillage, the use of cover crops, crop rotation diversification, agroforestry and organic matter restoration, contributes to the simultaneous achievement of environmental, economic and social effects. It is also important to implement the principles of the circular economy in the agricultural sector, in particular the effective use of organic waste and by-products.

It has been established that the integration of approaches to improving soil health in agricultural development and climate adaptation policies is insufficiently developed, which limits the possibilities of systematic implementation of innovative practices. In this context, it is necessary to form comprehensive soil resource management mechanisms that combine scientific knowledge, institutional tools and practical solutions at the level of farms and territorial communities.

Improving soil health should be considered not only as an agro-technological task, but as a strategic direction for ensuring climate resilience and long-term food security. Further research should be aimed at developing integrated soil resource management models adapted to regional conditions and the challenges of global transformations.

Bibliography:

1. Crista, F., Berbecea, A., Radulov, I., & Lato, A. (2020). Compendiu agrochimic. Eurostampa Timisoara, 87:93.
2. Domeignoz-Horta, L.A., Pold, G., Erb, H., Sebag, D., Verrecchia, E., Northen, T., Louie, K., Eloe-Fadrosh, E., Pennacchio, C., Knorr, M.A. et al. (2023). Substrate availability and not thermal acclimation controls microbial temperature sensitivity response to long-term warming. *Glob. Change Biol*, 29,1574–1590. DOI: https://doi.org/10.1111/gcb.16544
3. El Chami, D., Daccache, A., & El Moujabber, M. (2020) How Can Sustainable Agriculture Increase Climate Resilience? A Systematic Review. *Sustainability*, 12, 3119. DOI: https://doi.org/10.3390/su12083119
4. Emde, D., Hannam, K.D., Most, I., Nelson, L.M., & Jones, M.D. (2021). Soil Organic Carbon in Irrigated Agricultural Systems: A Meta-analysis. *Glob. Change Biol*, 27, 3898–3910. DOI: https://doi.org/10.1111/gcb.15680
5. FAO (2015). Soils help to combat and adapt to climate change by playing a key role in the carbon cycle. 2015 International year of soils. URL: https://reliefweb.int/report/world/soils-help-combat-and-adapt-climate-change
6. FAO (2021). Condition of land, soil and water resources. URL: https://openknowledge.fao.org/server/api/core/bitstreams/c53c6974-3125-4642-b4ed-693d36778008/content/src/html/chapter-1-1.html
7. HBLFA (2019). Klimafolgenforschung und Klimawandel-Anpassungsstrategien Beiträge der HBLFA Raumberg-Gumpenstein.
8. Kane, D., & Solutions, LLC. (2015). Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices; National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, LLC.: Washington, DC, USA, pp. 1–35.
9. Korobov, R., & Trombitsky, I. (2014). Vulnerability to climate change: Moldovan part of the Dniester basin. Intl. assoc. guardians of the Eco-TIRAS river. Kishinev. Tipogr. “Elan Poligraf”.
10. Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, 304, 1623–1627. DOI: https://doi.org/10.1126/science.1097396
11. Lal, R. (2015). Sequestering Carbon and Increasing Productivity by Conservation Agriculture. *J. Soil Water Conserv*, 70, 55A–62A. DOI: https://doi.org/10.2489/jswc.70.3.55A
12. Lehmann, J., Bossio, D.A., Kögel-Knabner, I. et al. (2020). The concept and future prospects of soil health. *Nat Rev Earth Environ*, 1, 544–553. DOI: https://doi.org/10.1038/s43017-020-0080-8
13. Liao, Q., Lu, C., Yuan, F., Fan, Q., Chen, H., & Yang, L. (2023). Soil carbon-fixing bacterial communities respond to plant community change in coastal salt marsh wetlands. Applied soil ecology, 189, 1–10. DOI: https://doi.org/10.1016/j.apsoil.2023.104918
14. McDowell, J. (2019). Cover Crops and Carbon Sequestration: Benefits to the Producer and the Planet. URL: https://cropwatch.unl.edu/2019/cover-crops-and-carbon-sequestration-benefits-producer-and-planet
15. Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., & Das, B.S. (2017). Soil Carbon 4 per Mille. *Geoderma*, 292, 59–86. DOI: https://doi.org/10.1016/j.geoderma.2017.01.002
16. Paul, O. (2021). How and why to adapt soil to climate change. Ecoclub. URL: https://ecoclubrivne.org/soil_adaptation/
17. Radulov, I., & Berbecea, A. (2023). Role of soil health in mitigating climate change. In Global Warming – A Concerning Component of Climate Change. *IntechOpen.* DOI: https://doi.org/10.5772/intechopen.1002402
18. Seidu, M. (2016). The Role of Soil in Climate Change Mitigation and Adaptation via Carbon Cycle. Working Paper-2016. URL: https://www.researchgate.net/publication/311665199_Working_Paper-2016_The_Role_of_Soil_in_Climate_Change_Mitigation_and_Adaptation_via_Carbon_Cycle#fullTextFileContent
19. Shibabaw, T., Rappe, M.O., & Gärdenäs, A.I. (2023). The combined impacts of land use change and climate change on soil organic carbon stocks in the Ethiopian highlands. *Geoderma Regional*, 32, e00613. DOI: https://doi.org/10.1016/j.geodrs.2023.e00613
20. Telo da Gama, J. (2023). The Role of Soils in Sustainability, Climate Change, and Ecosystem Services: Challenges and Opportunities. *Ecologies*, 4, 552–567. DOI: https://doi.org/10.3390/ecologies4030036
21. Ursu, A. (2011). Solurile Moldovei. Chisinau, Î.E.P. Ştiinţa, 324 p.
22. Verband der Landwirtschaftskammern. (2019). Klimawandel und Landwirtschaft: Anpassungsstrategien im Pflanzenbau (2. Auflage) [Brochure]. Thüringer Landesamt für Landwirtschaft und Ländlichen Raum. URL: https://www.tlllr.de/www/daten/agraroekologie/klima/klimawandel/vlk_klima_pflanze19.pdf [in Deutch].
23. Wan, Y., Lin, E., Xiong, W., Li, Y., & Guo, L. (2011). Modeling the impact of climate change on soil organic carbon stock in upland soils in the 21st century in China. *Agriculture, Ecosystems & Environment,* 141(1-2), 23–31. DOI: https://doi.org/10.1016/j.agee.2011.02.004
24. Wang, Y., Li, C., & Hu, S. (2023). Land use effects on the dynamics of soil carbon, nitrogen and microbes in the water-wind erosion crisscross region of the northern Loess Plateau. *Pedosphere*, 33, 1–17. DOI: https://doi.org/10.1016/j.pedsph.2023.03.019
25. Xu, T., Shen, Y., Ding, Z., & Zhu B. (2023). Seasonal dynamics of microbial communities in rhizosphere and bulk soils of two temperate forests. Rhizosphere, 25, 1–9. DOI: https://doi.org/10.1016/j.rhisph.2023.100673

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