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Can improving soil health enhance agricultural sustainability and resilience to climate change?

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The paper is devoted to the currently relevant problem of achieving sustainable development and minimizing the consequences of climate change by improving soil health. The authors aimed to determine whether improving soil health can enhance agricultural sustainability and resilience to climate change. A theoretical justification is provided for three concepts: soil health, sustainable development goals, and climate change, through an understanding of soil functions. Soil plays a key role in conserving nutrients, regulating water balance, reducing erosion, and mitigating greenhouse gas emissions. An attempt has been made to analyze soil health indicators to understand how they can be influenced to prevent climate change. Depending on the importance and complexity of monitoring soil health indicators, they were divided into three levels of observation. Level I is for baseline indicators that require continuous, more frequent monitoring (e.g., annually): OM and soil moisture content, pH, bulk density, soil texture and structure, visual state, and earthworm count. II level is for more detailed and required laboratory analyses: potentially mineralized nitrogen content, cation exchange capacity, aggregate stability, electrical conductivity, water holding capacity indicators, and microorganism biomass. III level is for highly specialized laboratory research, which is held less frequently: microbial ratio (bacteria : fungi), C : N, soil respiration (CO_2 emission), enzyme activity, microbiome genetic analysis, soil fauna biodiversity index, infiltration capacity. Based on the research, we propose addressing the issues of soil health, sustainable development, and climate change mitigation through measures to improve water retention capacity, maintain biodiversity, reduce soil erosion and degradation, and mitigate greenhouse gas emissions from agriculture, as well as adapt agricultural systems. The main thing is that the soil must preserve its functions for future generations. Be that as it may, food security will still be a basic need of all mankind. People will satisfy all other needs only when their biological needs are regular and satisfied.

Keywords: humus, fertilizer, mycorrhizae, microbiota, soil fertility, yield, ecosystem.

Чи може покращення здоров'я ґрунту підвищити сталий розвиток сільського господарства та стійкість до зміни клімату?

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Стаття присвячена актуальній на сьогодні проблемі досягнення сталого розвитку та мінімізації наслідків зміни клімату шляхом покращення здоров'я ґрунту. Автори мали на меті визначити, чи може покращення здоров'я ґрунту підвищити стійкість сільського господарства та стійкість до зміни клімату. Наведено теоретичне обґрунтування трьох концепцій: здоров'я ґрунту, цілей сталого розвитку та зміни клімату через розуміння функцій ґрунту. Ґрунт відіграє ключову роль у збереженні поживних речовин, регулюванні водного балансу, зменшенні ерозії та пом'якшенні викидів парникових газів. Було зроблено спробу проаналізувати показники здоров'я ґрунту, щоб зрозуміти, як на них можна впливати для запобігання зміні клімату. Залежно від важливості та складнощів моніторингу за індикаторами здоров'я ґрунту, вони були поділені на три рівня за спостереженнями. І рівень призначений для показників базового рівня для постійного більш частого моніторингу: вміст органічної речовини (гумусу) та вологи ґрунту, pH, об'ємна щільність, текстура та структура ґрунту, візуальний стан, кількість дощових черв'яків. ІІ рівень призначений для більш детальних лабораторних аналізів: вміст потенційно мінералізованого азоту, ємність катіонного обміну, стабільність агрегатів, електропровідність, показники вологоутримувальної здатності, біомаси мікроорганізмів. ІІІ рівень призначений для вузькоспеціалізованих лабораторних досліджень і які проводяться більш рідше: мікробне співвідношення (бактерії : гриби), C : N, дихання ґрунту (виділення CO_2), активність ферментів, генетичний аналіз мікробіому, індекс біорізноманіття ґрунтової фауни, інфільтраційна здатність. На основі дослідження ми пропонуємо вирішувати проблеми здоров'я ґрунту, сталого розвитку та пом'якшення наслідків зміни клімату заходами з секвестрації вуглецю, покращення водоутримувальної здатності, підтримки біорізноманіття, зменшення ерозії та деградації ґрунту, скороченням викидів парникових газів від сільського господарства та адаптації сільськогосподарських систем. Головне, щоб ґрунт зберігав свої функції для майбутніх поколінь. Як би там не було, продовольча безпека все одно залишатиметься базовою потребою всього людства. Люди задовольнятимуть усі інші потреби лише тоді, коли їхні біологічні потреби будуть регулярними та задоволеними.

Ключові слова: гумус, добриво, мікориза, мікробіота, родючість ґрунту, врожайність, екосистема.

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Today, in almost any field of research, any publication necessarily references the compliance of the authors' proposal and development with the Sustainable Development Goals. The general understanding of all 17 goals, which comprise 169 tasks [1], is often fixed as indisputable, so it does not need to prove its relevance. This is true because civilizational development is impossible without a perspective plan. Perspectives appear only if you strive for their implementation. This applies to sustainable development, particularly its thirteenth goal. According to the current report, "The Sustainable Development Goals Report. Special edition" [2], it identifies among the causes of climate change "the use of exhausting methods of land use and adherence to irrational patterns of consumption and production." We see a reference to land use that directly affects soil health as "the ability to function as a living ecosystem capable of supporting plants, animals and people" [3].

Unfortunately, the report mentioned above illustrates that the work to achieve Goal 13 does not coincide with the plan and has certain problems, including regression in some indicators. Therefore, the world community should make more efforts to realize this goal. We aim to demonstrate in this work that it is possible to achieve this by enhancing the health of the soil, similar to other mechanisms. To support this prediction, a quote from Raghavendra et al. [4] can be added, where even in the definition of the term, its connection to sustainable agriculture is given: «Soil health indicators are a composite set of measurable physical, chemical, and biological attributes which relate to functional soil processes and are being used to evaluate soil health status)». Also, Doran [5] consistently points to the optimization of soil functions and resources as sustainable agricultural practices that support soil health.

Soil health is a complex concept that is balanced by various indicators. Allen et al. [6] define it as balanced and influencing performance. The perspective of using land fertility indicators is highlighted in the definition presented by Lehmann et al. [7]: "continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply-chain management". The definition of soil health is inextricably linked to its ability to perform its primary functions and its relationship to various subjects, as outlined in the above definition: plants, animals, and people. So, the more effectively the soil will be able to realize its functions, the more effective will be the sustainability of its use for agricultural purposes.

Soil health can be assessed using specific indicators and specific methods. Summarizing the research of Kibblewhite et al [8], we schematically depicted the following methods of soil health assessment and analysis (*Fig. 1*).

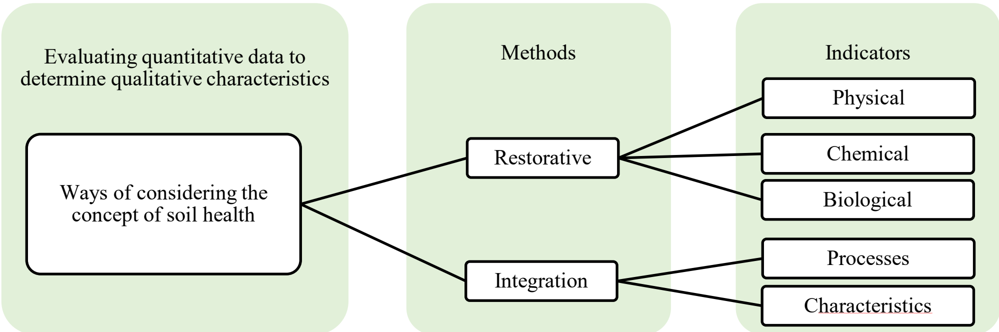

Fig. 1. Methods and indicators of soil health assessment (construction based on literary data).
Source: [8].

Theoretically, in this case, we can discuss assessing quality indicators and their interaction, which form the processes and their consequences, which will be decisive. To develop a system of indicators that need to be influenced to improve soil health, it is necessary, first of all, to identify the key numbers to focus on when enhancing soil use for sustainability (*Table 1*).

In a natural ecosystem unaffected by humans, the carbon balance is positive; plants photosynthesize, their residues accumulate in the soil and turn into humus [9]. When farmers begin farming in the fields, they can disrupt the natural balance, potentially leading to a threat of climate change [10]. When farmers harvest crops from the field, the energy in the form of organic compounds and residues is removed, which should have been absorbed by the soil, and it also removes phosphorus, potassium, and trace elements [11]. Therefore, the more intensive the farming system, the more humans deplete the soil.

Table 1
Some indicators of soil health that may be associated with sustainability and the mitigation of climate change

Indicators	Function	Task
Primary productivity	Safeguarding the environment, regulating biological populations; water cycle; providing habitat	Production of biomass
Organic substances and carbon; potentially mineralized nitrogen	Cyclicity of elements and organic substances; water cycling	Supply of nutrients, climate regulation
Water holding capacity	Provision of habitat and regulation of biological population	Temperature regulation, water quality and supply
Soil texture and stability	Maintenance of good soil structure	Erosion control

Source: [4, 6].

Soil organic matter is not only humus, but also plant and animal remains, as well as living flora and fauna: from bacteria to field mice. The organic components of the soil are constantly in a state of transition from one form to another. Plants take mineral elements from the soil, their residues become food for animals, insects and microorganisms [12]. Complete decomposition of the remains of plants and all those who fed on them leads to the release of mineral elements needed by plants, as well as to the accumulation of additional organic matter in the form of humus compounds [13]. This is a positive carbon balance in a healthy ecosystem. Climate change and carbon balance always go hand in hand [14].

Agribusinesses are not increasing the productivity of ecosystems, but are using more and more mineral nutrients and pesticides to combat the consequences of declining soil productivity. Unhealthy crop rotation [15] leads to an increase in the use of chemical pesticides (especially first-generation ones), which alters the qualitative composition of soil biota. As a result, the simplest unicellular organisms, as well as worms and insects, die, the diversity of the microbial world decreases, and mycorrhizal fungi disappear. There is also a change in the ratio of beneficial to harmful microorganisms, and pathogenic fungi and bacteria begin to predominate in number. Excessive use of mineral nutrition while reducing organic matter reserves in the soil leads to soil salinization [16]. A stable ecosystem, formed from everything available in this climatic zone, will significantly improve the circulation of substances and stabilize climatic changes.

The reproduction of pathogens on vegetative plants causes epiphytes of diseases (excessive spread of the disease). With monocultures and two-field crop rotations, where the same list of pathogens accumulates from year to year, against the backdrop of a reduction in the number and diversity of beneficial microflora, there is an uncontrolled increase in the number of pathogens. Thus, more chemicals are needed to protect the plant. The same applies to pest control, particularly in the context of a decline in the biodiversity of entomophages [17]. The lack of labile organic matter, combined with an excessive amount of mineral nutrition, forces the microbiocenosis of the soil to utilise humus as a source of carbon and energy. Although humus is a very stable structure that is not easily degraded by microbes, microbes find a way to feed on it when necessary. Thus, mineralization of organic matter begins to prevail over condensation (formation of new organic compounds), and the soil increasingly loses organic matter.

To monitor the health of the soil, it is necessary to monitor the state of the soil constantly. In addition to agrochemical analysis, microbiological analysis of the soil is also necessary. This will allow monitoring the following critical components, in particular: the dynamics of changes in the content of organic matter in the soil; important structural indicators (the degree of compaction, moisture content, erosion); changes in soil microflora, in particular the accumulation of pathogens, reduction in the number of functional groups of microorganisms [18].

The problem can be solved in the future by restoring the carbon balance. First, it is necessary to compensate for carbon losses due to the use of covering crops or composts, and second, it is necessary to restore the soil microflora, which should transform this organic matter into humus compounds. The first step in this process is to refuse burning plant residues and instead promote their controlled decomposition with the aid of microbial preparations, which aim to enhance the soil microbiota.
Soil biota consists of several elements. Among which: the smallest parts are bacteria, actinomycetes, fungi, and the larger ones are the simplest primary-mouthed amoebas, ciliates, which feed on microorganisms. Next comes mesofauna (insects, worms), which feed on protozoa, and macrofauna, all the animals that live in this area. Therefore, to restore the normal flora and fauna of the soil, it is necessary to start with the lowest link – microorganisms [19]. Correction of soil dysbacteriosis entails the restoration of other links in the food chain that are disturbed by “extensive” agriculture.

In the presence of a sufficient amount of available organic substances in the soil, healthy flora and fauna can influence the soil’s physical and chemical characteristics [20, 21]. Loosening, desalination, normalization of acidity, and an increase in moisture content – all desirable phenomena for every agronomist can be achieved due to soil improvement. After all, a stable ecosystem can maintain soil productivity, control the number of pests and pathogens, protect plants from stress factors, and reduce the risk of agriculture. What farmers will have as a result is healthy soil, and therefore the opportunity to implement agriculture, let’s say, “without fanaticism” from the point of view of the use of harmful substances and components.

Many experts believe it is necessary to switch to plough-less soil cultivation to prevent moisture and yield loss [22]. In general, practices of zero or minimal tillage, cover crops, and agroforestry contribute not only to soil conservation but also prevent soil degradation, which is an additional factor in climate change and, at the same time, is influenced by it [23]. That is, these indicators are interconnected and cause mutual influence.

Don’t forget that soil management practices that improve soil health can also reduce greenhouse gas emissions from agriculture. For example, improving nitrogen management reduces emissions of N_2O, a potent greenhouse gas. What can be done? It is essential to pay attention to the forms of nitrogen available to plants, which are primarily water-soluble, including nitrates, ammonium, and some amino acids [24].

There may be other forms, but these are the most important. In total, about 54 different amino acids and amino acid-type compounds are identified as available to plants. There are many methods for determining nitrogen in the soil. The burning method is one of the most famous [25]. This method provides information on total nitrogen (organic + inorganic) and total carbon. Also known is the method of extraction with a solution of potassium chloride, which yields the total amount of inorganic nitrogen (nitrates + ammonium). Understanding the value of total nitrogen (organic + inorganic), we can subtract the value of inorganic nitrogen (nitrates + ammonium) from it; this way, we will obtain the organic nitrogen value. In the context of the “Soil Health” principles, nitrogen extracted with clean water (water extraction) is currently analyzed. After extraction from the aqueous extract, organic nitrogen, nitrate and ammonium are analyzed; all of these forms of nitrogen are thought to be available to plants because they are water-extractable (dissolved in water). In a natural stable environment, the dominant form of organic nitrogen in the soil is amino acids; therefore, from the point of view of "Soil Health", the analysis of water-soluble organic nitrogen [26] is a successful and informative method. If we do not consider the introduction of nitrogen fertilizers, there are two main sources of nitrogen entering the soil: as a product of the vital activity of soil biomass, and from organic matter [27].

All this nitrogen can also be considered when considering the need for fertilizers. It is believed that one to three percent of nitrogen enters the soil during mineralization from organic matter. Standard agrochemical soil analysis uses various solutions (e.g., ammonium acetate, DTPA, Mehlich III, and others) to measure plant-available nutrients and total plant-absorbable minerals. To analyse the total amount of nutrients (most of which are unavailable forms that can be considered a mineral reserve), the decomposition of samples (digestion) is used; therefore, let's not confuse these two different chemical methods. But how do plants get these unavailable forms of nutrients? Answer: only thanks to microorganisms and the mycorrhizal connection. All the necessary mineral nutrients, which are critical for plant health, but are in an unavailable forms, can be obtained by plants only through the association with mycorrhizae [28]. Nature provides us with all these nutrients for free, but the most important thing is that we need to understand how these substances are released (become available to plants). The percentage of bacterial colonization can be measured by microscopy and microscopic techniques, which are very accurate but time-consuming and expensive. Plant roots (as working material) are used to identify this percentage of bacterial colonization, because that is where nutrient exchange takes place [29].

However, two new and very sensitive methods exist: "Soil respiration" and the PLFA test (Phospholipid Fatty Acids Test – analysis of phospholipid fatty acids). Soil respiration provides information on the total number of microbial communities based on the amount of carbon dioxide released from the soil [30]. The soil sample is placed in a small glass jar, moistened with a small amount of water, and then closed with a lid. It is kept in an incubator for 24 hours in a warm environment. After 24 hours, the amount of carbon dioxide released from this soil is measured. The PLFA test (Phospholipid Fatty Acid Test) is an analysis designed to detect total microbial biomass using specific biomarkers that are unique to certain microbial groups [31]. These biomarkers are quantified by gas chromatography and provide information on the following soil communities: bacteria (gram-positive and gram-negative), fungi, mycorrhizae, actinomycetes, nitrogen-fixing bacteria, and protozoa.

We have conventionally divided soil health indicators into three levels (***Fig. 2***).

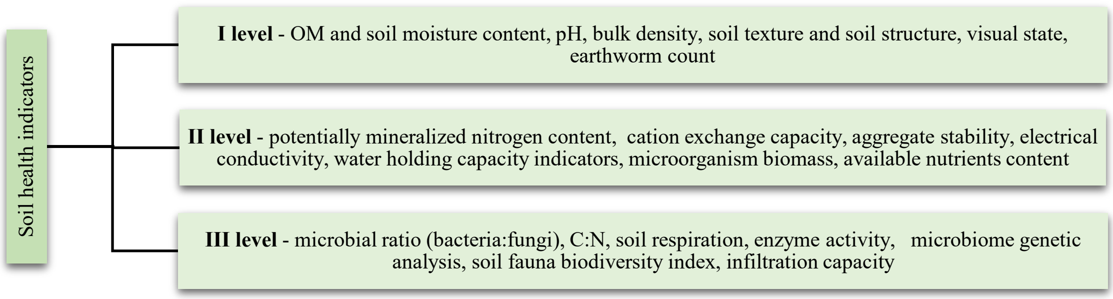

Fig. 2. Classification of soil health indicators depending on the complexity of the measurement, the availability of techniques, and the depth of interpretation
Source: [4, 27, 29, 32, 33].

Level I is the baseline level for annual monitoring. The II level is for more detailed and required laboratory analyses. The III level is for highly specialized laboratory research.

It is obvious that achieving soil health and implementing sustainable agricultural practices will help minimize the negative consequences of climate change (***Fig. 3***).

It is possible to combine the proposed measures and predict their impact on the main trends in climate change that we are currently observing. For example, these include an increase in air temperature and the melting of glaciers, an increase in extreme weather conditions (such as droughts, downpours, and hurricanes), a rise in carbon dioxide concentration, and a decline in biodiversity in various ecosystems. All this affects all areas of human activity and the human body. An increase in the number of diseases caused by climate change can lead to a deterioration in nations' overall health and a reduction in life expectancy. Climate change can lead to population migration, resource conflicts, economic losses due to reduced harvests, and infrastructure destruction, necessitating significant adaptation and recovery costs.

Think about this: total human consumption of plant-based foods in developed countries is about 500–600 kg [34]. Food waste, on average, per person is 79–132 kg. If you add garden waste and other biodegradable materials to this amount, the total waste will increase to 200–300 kg per year per person. People on the planet need to be fed, and at the same time, the fertility of the soil needs to be maintained.

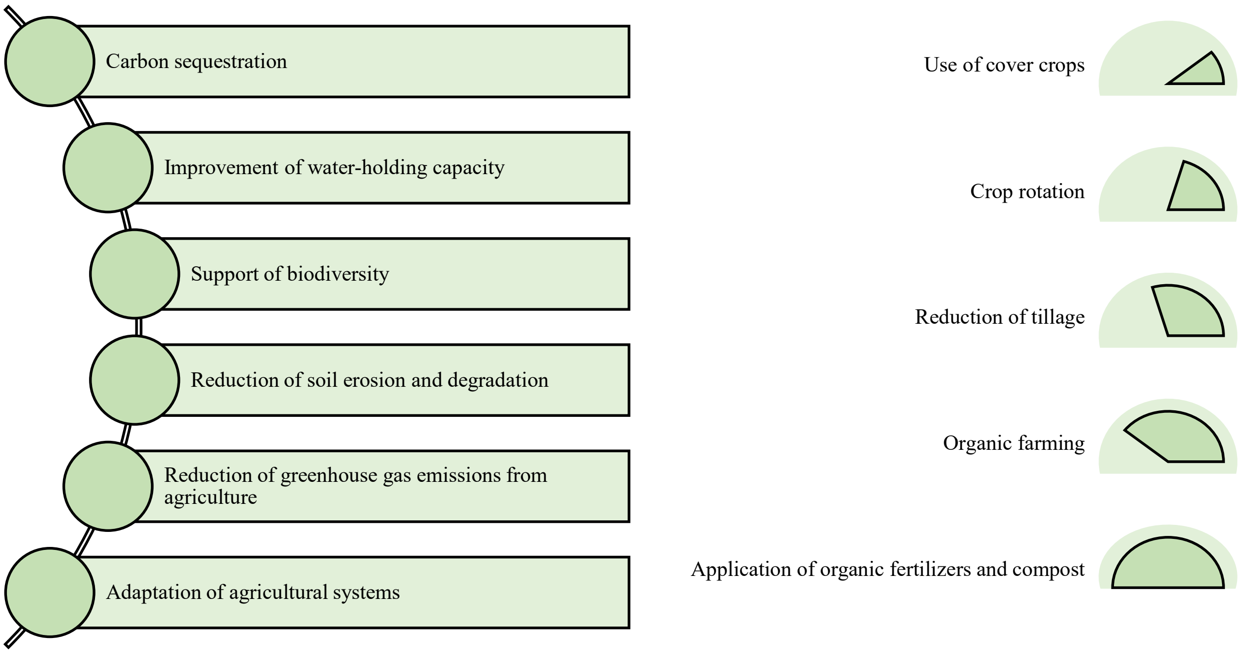

Fig. 3. Means of achieving soil health and practising sustainable agriculture, which can influence the minimization of the negative consequences of climate change
Source: [20, 28].

Conclusions

Soil health, sustainable development, and climate change mitigation are interrelated and require a comprehensive approach to address their interconnected challenges. The main solutions can be reducing greenhouse gas emissions, adapting to new climatic conditions, and introducing sustainable agriculture practices. The primary concern is that the soil must retain its functions for future generations. Be that as it may, food security will still be a basic need of all mankind. People will satisfy all other needs only when their biological needs are normal and satisfied.

Improving soil health is a critical tool for increasing agricultural sustainability and its adaptability to climate change. Soil restoration is not a short-term measure, but a long-term investment in the sustainability and productivity of agroecosystems. Farmers who implement biocentric technologies not only achieve better yields, but also reduce their farms' vulnerability to climate risks.

Conflict of interest

The authors state that there is no conflict of interest.

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