EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(4), 229–236
https://doi.org/10.12912/27197050/201190
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Received: 2025.01.24
Accepted: 2025.02.21
Published: 2025.03.01

Changes in soil fertility in the southern steppe zone of Ukraine

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ABSTRACT

The article explores the significance and impact of organic matter on the fertility of dark chestnut soil and black soil in the southern regions under irrigation and without irrigation. The aim was to determine the effect of organic fertilizers on the content of humus, water-physical properties, and other fertility indicators. Research conducted at the Institute of Irrigated Agriculture established that without manure in crop rotations with alfalfa, the organic matter content decreases, especially in irrigated plots. After 30 years of observation, the maximum organic matter content was found with optimal application of mineral fertilizers and manure. Irrigation positively affects the mineralization and humification of organic substances, but without irrigation, the humus content is higher due to significantly lower nutrient leaching. Without the application of mineral fertilizers, there is a decrease in total forms of nitrogen, phosphorus, and potassium, including in irrigated soils. Mineral fertilizers increase phosphorus content, but potassium remains at a low level. The results indicate the necessity of a systematic approach to fertilization to maintain and preserve soil fertility. Applying organic materials, such as wheat straw, improves the soil's water absorption capacity and promotes microbiota development. Growing alfalfa accumulates a significant amount of organic matter and biological nitrogen; however, in the absence of livestock farming, it is suggested to sow annual leguminous crops, which are crucial for sustainable production and enhancing soil fertility. Irrigation significantly increases crop yields; however, it also substantially increases nutrient leaching, necessitating additional compensation. The use of available organic materials improves the physical properties of the soil, particularly its structure and water absorption capacity, which is critically important in increasing aridity and climate change prevention. A comprehensive approach to soil fertility management is proposed, including the mandatory use of organic fertilizers and the cultivation of leguminous plants in crop rotations.

Keywords: soil fertility degradation, organic fertilizers, climate change, restoration of soil fertility, multi-crop rotations, perennial leguminous grasses, organic matter, ecological sustainability, productivity.

INTRODUCTION

Ukraine is recognized around the world for its high-yielding soils for land use. The soil and climatic conditions of the southern region, along with established technologies, allow for the cultivation and sustainable productivity of almost all crops. However, in recent decades, the leading indicators of soil fertility have significantly deteriorated and degraded. Several factors have caused this: deviations from strict adherence to the fundamental laws of agriculture (violations of justified crop rotation in crop rotations, soil cultivation practices, etc.), insufficient application of fertilizers, especially organic ones (the use of organic matter has decreased significantly to 0.5–0.7 tons per hectare) [Veremeenko and Furmants, 2014; Veremeyenko and Semenko, 2019; Balyuk et al., 2017; Gamayunova et al., 2020], significant climate changes (increased temperature regime with inadequate and uneven precipitation), and now military actions have also been added to these reasons. Thus, modern agriculture faces several ecological, social, and economic challenges that require solutions [Hospodarenko et al., 2019; Boinchan and Dent, 2020; Nasibov et al., 2024]. It is necessary to assess and recognize the causes and outline correct approaches to a more sustainable agricultural system [Gamajunova et al., 2021; Hamajunova et al., 2023].

The primary task should be to restore soil fertility, as soil is the primary means of production. The soil condition and adherence to agronomic practices directly affect the quantity and quality of the produced crops, the farm's economy, and the environment's state.

Changes in the main characteristics of soil fertility are closely related to climate change. The climate is undergoing significant fluctuations due to rising CO_2 emissions and land use practices, mainly deforestation, systematic soil cultivation, and burning fossil fuels. The assimilation of biological carbon by plants improves soil and water quality, increases biodiversity, enhances plant productivity, and provides other factors that allow adaptation to global warming. Moreover, it is most beneficial when plants utilize excess carbon during photosynthesis, sequestering and storing it in the soil as living biomass and organic carbon. This will help prevent, mitigate, and slow down global warming. In addition to climate change, carbon sequestration—its binding by plants—addresses another critical issue: it alleviates soil degradation processes [Skrylnyk et al., 2018; Lopushniak, 2011].

Long-term research by many scientists has shown that the more crops are included in crop rotation, the better the quality of organic matter in the soil. Including perennial legumes enriches the soil with valuable organic matter, organic carbon, and nitrogen. All these components are essential for the development of soil microorganisms, which in turn decompose the labile fractions, releasing available nutrients from organic residues, transforming them into microbial biomass and a stable fraction of soil organic carbon that binds with clay minerals and is not mineralized [Boinchan and Dent, 2020; Gamayunova et al., 2024].

Maintaining soil fertility and structure can be achieved by replenishing fresh organic matter. Moreover, the more diverse crops are grown in crop rotation, the higher the quality and variety of the organic matter will be. Perennial grasses significantly impact this, as they enrich the soil with organic matter and provide biological, free nitrogen. On the other hand, if crop rotation is practically absent and many row crops are grown with only mineral fertilizers applied, the content of organic matter in the soil decreases, along with the total (gross) nitrogen [Hryhoriv et al., 2024; Kovalenko et al., 2024; Gamayunova and Sydiakina, 2023].

Climate change and soil fertility are closely interconnected. Climate changes significantly fluctuate due to the increase in CO_2 emissions, the burning of fossil fuels (which has increased due to military actions), and the direction of land use practices, mainly deforestation, systematic soil cultivation, etc. Under such conditions, it is necessary to enhance plants' assimilation of biological carbon. This will improve the quality of soils and water, increase biodiversity, enhance plant productivity, and other factors that allow adaptation to global warming. Moreover, it is most beneficial when plants utilize excess carbon during photosynthesis, binding and storing it in the soil as living biomass and organic carbon. This will help prevent, mitigate, and slow down global warming [Boinchan and Dent, 2020].

In addition to climate change, carbon sequestration (the binding of carbon by plants) addresses another critically important issue – it alleviates soil degradation processes. Achieving a sufficient amount of organic matter in the soil is crucial. The more crops are grown in crop rotation, the better and more valuable organic matter will enter the soil. Including perennial legumes in crop rotations enriches the soil with valuable organic matter, organic carbon, and biologically available nitrogen. All these components are essential for developing soil microorganisms, which decompose mobile fractions, release available nutrients from organic residues, and convert them into microbial biomass and stable fractions of soil organic carbon that bind with clay minerals and do not mineralize [Boinchan and Dent, 2020].

The study aims to determine organic matter's role in shaping fertility's main characteristics in dark chestnut soils and black soils of the south under both long-term and short-term irrigation and non-irrigation conditions. The research results may serve as a basis for developing practical technological elements to restore soil fertility in the context of climate change.

MATERIAL AND METHOD

To determine the role of organic matter on the leading indicators of the fertility of dark chestnut soil and southern chernozem in long-term and short-term experiments under irrigation and rainfed conditions. The study of changes in the leading indicators of soil fertility under irrigation and rainfed conditions was conducted at the NNPZ MNAU and the Institute of Irrigated Agriculture. Chemical analyses were performed according to the following standards: sampling methods according to DSTU ISO 6497:2005; determination of total nitrogen using the Kjeldahl method - DSTU ISO 5983-2003; phosphorus according to DSTU ISO 6491:2004; potassium according to DSTU ISO 7485:2003. The method for determining organic matter - DSTU 4289:2004; humus content (using the Turin-Kononova method); the structural-aggregate composition of the soil was determined by the sieve method in the modification of N. I. Savvinov (according to DSTU 4744:2007); granulometric and macroaggregates composition was assessed using the pipette method in the modification of N. A. Kachinsky (according to DSTU 4730:2007, DSTU 4728:2007).

RESEARCH RESULTS

Even in justified and recommended crop rotations for the region with alfalfa, the content of organic matter and humus may decrease without adding manure. This occurs more significantly under irrigation (Table 1).

In a 7-field crop rotation (lucerne for three years, winter wheat, corn for grain, corn for silage, winter wheat), after 30 years of research, the amount of organic matter and humus reached its highest levels due to the application of the optimal dose of complete mineral fertilizer for each crop in the rotation, along with a one-time application of 80 t/ha of semi-rotted manure under irrigated conditions and 40 t/ha without irrigation under corn for silage.

It should be noted that under irrigation, the total humus content significantly decreases, especially without applying fertilizers, during the first 20 years; this process gradually slows down in the subsequent period. After 30 years, even with the application of NPK fertilizers for the crops, we achieved the initial humus content of 2.26%, which was present at the start of the experiment. The humus content was lower than the initial level in other nutrition variants—where individual mineral fertilizers were applied unilaterally and in the unfertilized control soil. Only applying optimal doses of complete mineral fertilizers and a one-time application of semi-rotted manure during the crop rotation slightly increase total humus in the 0–30 cm soil layer.

It is noteworthy that without irrigation, in the same crop rotation, the humus content without fertilizer in the control remains higher compared to its irrigated counterpart. However, the variant combining NPK and manure contained somewhat less. This is related to the lower amounts of mineral fertilizers and manure applied, as well as the processes of mineralization of post-harvest root residues of the crops and manure due to unstable optimal moisture availability in the soil. This assumption is confirmed by the soil's organic matter content and water-soluble humus. Without irrigation, due to significantly lower yields, plants have fewer post-harvest root residues, meaning less enters the soil. However, the freshest organic matter enters the soil in variants where recommended mineral fertilizers are applied under crop rotations and manure (once per rotation). The highest levels of water-soluble humus were determined precisely with this combination of fertilization systems in long-term irrigated soil and without irrigation.

This indicator changes primarily under prolonged fertilization and agrotechnical measures

Table 1. The content of organic matter and humus in the 0-30 cm layer of dark chestnut soil under the influence of prolonged irrigation

Version	Content of organic matter, %		Content of humus, %		Content of water-soluble humus, %	
	Irrigation	Without irrigation	Irrigation	Without irrigation	Irrigation	Without irrigation
Without fertilizers, control	7.63	6.34	2.13	2.20	24.47	23.12
P_2O_5	7.71	6.38	2.19	2.23	26.68	24.72
N	7.77	6.49	2.23	2.24	26.18	24.97
NPK	8.11	6.75	2.26	2.25	28.60	25.85
NPK + manure	8.23	7.12	2.36	2.32	29.17	27.38

during cultivation. The content of water-soluble humus characterizes the presence of mobile organic matter in the soil that is at the initial stages of humification and will eventually transform directly into humus. Irrigation positively influences these processes of organic matter transitioning into humus, as mineralization and humification occur more intensively due to sufficient moisture in the soil, which prevents these processes from being hindered as they are during periods of moisture deficiency.

Without applying mineral fertilizers over an extended period, the content of gross forms of nitrogen, phosphorus, and potassium in the soil changes significantly (Table 2). Even in a crop rotation with lucerne, total nitrogen in the 0–30 cm soil layer decreases relative to the initial content: from 0.116% to 0.108% (without irrigation) and 0.112% with irrigation. In the latter variant, this indicator was also higher due to the activation of microbiological processes, including the symbiotic activity of nodule bacteria when growing lucerne under optimal moisture conditions for both the soil and the plants. This is also evidenced by the maximum amount of gross nitrogen in the 0–30 cm soil layer, resulting from the systematic application of mineral fertilizers for each crop in the rotation (at recommended rates for the zone). The soil's gross phosphorus content changed somewhat differently under prolonged irrigation and fertilization. Without applying mineral fertilizers over thirty years, its quantity significantly decreased in rainfed soil and even more so in irrigated soil. In variants with the application of mineral fertilizers at recommended rates for each crop in the rotation, the content of P_2O_5 significantly increased compared to the initial level, particularly in non-irrigated soil, even though the doses of fertilizers applied were lower than in the irrigated variant. This is related to the levels of yield of crops and, accordingly, the significantly greater removal of nutrients, including phosphorus, during irrigation. For instance, when growing lucerne without irrigation and fertilizers, the average hay yield over five rotations was 14.4 t/ha. In contrast, it was 23.6 t/ha in irrigated conditions without fertilizer application, which is 63.9% more. Applying mineral fertilizer $N_{30}P_{60}K_{30}$ without irrigation resulted in a 16.1 t/ha yield, while $N_{30}P_{100}K_{30}$ under irrigation produced 31.8 t/ha, or nearly double the amount. The accumulation of root biomass and post-harvest residues left in the soil after harvesting replenishes it with valuable organic matter and biologically fixed nitrogen. At the same time, although leguminous plants, particularly lucerne, contribute to the release of fixed (bound) unavailable forms of phosphates from the soil, the content of gross phosphorus in the 0-30 cm soil layer was somewhat lower compared to the analogous variant without irrigation. With mineral fertilizers, this indicator increased to 0.138% and 0.142%, respectively, from an initial content of 0.124%.

The content of gross potassium decreased in soil that has not been fertilized for a long time, without and with irrigation. After 30 years of experimentation, its content in the 0-30 cm soil layer amounted to 1.56% and 1.72%, while at the time of establishing the experiment, it was 1.97%. The application of mineral fertilizers for each crop in the non-irrigated variant had practically no effect on the final indicator relative to the initial K_2O content, which was 1.99%, while under systematic irrigation and fertilization, it significantly decreased to 1.55%, or by 27.1%. This pattern can be explained by the productivity levels of all grown crops under conditions that meet their moisture needs and a significant difference between the total potassium removal with the yield and the application of potassium fertilizers. According to long-term studies on potassium balance in soil, researchers have concluded that it forms a negative balance in most soil types, regardless of agricultural conditions.

Table 2. Changes in the content of gross forms of NPK in the soil under the influence of prolonged (30-year) irrigation and fertilization, %

Research option	N	P_2O_5	K_2O
For the period of establishment of the experiment	0.116	0.124	1.97
Without irrigation, without fertilizers	0.108	0.100	1.56
Without irrigation + NPK for each crop rotation	0.117	0.142	1.99
Irrigation, without fertilizers	0.112	0.095	1.72
Irrigation + NPK for each crop rotation	0.137	0.138	1.55

Studies have shown that prolonged irrigation slightly increases soil porosity compared to its non-irrigated counterpart. This is observed for both the 0–30 cm and 0–100 cm soil layers (Fig. 1). Conversely, as soil porosity decreases with prolonged irrigation, bulk density and specific density gradually increase (Fig. 2).

As the data presented in Figure 2 indicate, both bulk and specific density increase with irrigation in the 0–30 cm and 0–100 cm soil layers during the studies conducted under a scientifically justified crop rotation involving alfalfa cultivation over three years and the application of 80 t/ha of semi-rotted manure per rotation.

The water-physical indicators of the 0–30 cm soil layer significantly improve with the addition of organic matter, as established by our research (Table 3). The application of manure and incorporation of the pea-oat mixture as green fertilizer, both separately and with the addition of $N_{40}P_{30}$, positively influenced all soil fertility indicators that were determined. The number of water-stable aggregates with the application of fresh organic matter increased to 35.2–38.2%, compared to 28.3% in the non-fertilized soil. Total porosity and water absorption capacity also increased while bulk density decreased. These are the most important indicators of soil fertility, as ensuring

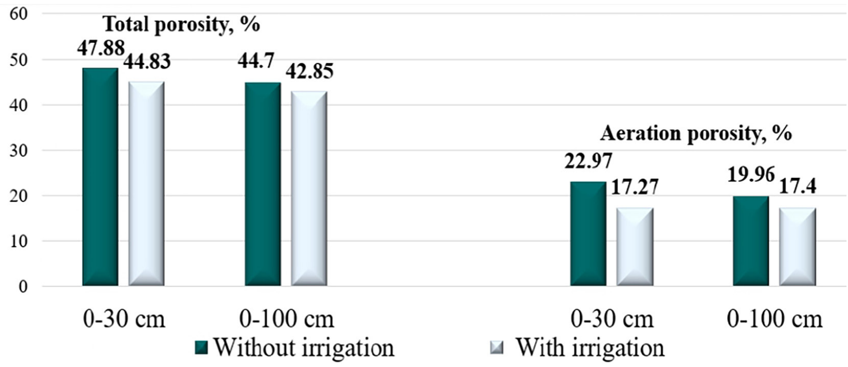

Figure 1. The effect of prolonged irrigation (30 years) on soil porosity compared to non-irrigated counterparts, %

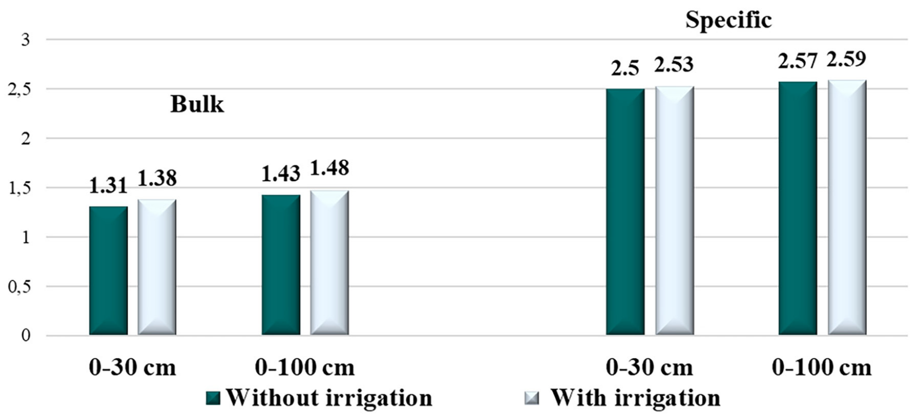

Figure 2. The effect of prolonged irrigation on the bulk density of dark chestnut soil compared to non-irrigated plots, g/cm³

Table 3. The effect of organic fertilizers on the content of water-stable aggregates, bulk density, and porosity of the 0–30 cm soil layer (average for 2021–2023)

Experimental variant	Number of water-stable aggregates, %	Bulk density, g/cm³	Total soil porosity, %	Water absorption in the 3rd Hour, mm
Without fertilizers	28.3	1.28	51.6	24.4
Manure 30 t/ha	35.8	1.24	54.4	35.1
Pea-oat mixture	36.4	1.21	54.7	36.3
Pea-oat mixture + $N_{60}P_{40}$	38.2	1.19	54.8	38.0

soil moisture is crucial for achieving stable crop yields under increasing aridity and temperature variations. Precipitation, which falls irregularly and in small amounts, must be maximally accumulated and retained in the soil, promoting effective use by plants and avoiding unproductive losses due to evaporation.

The water absorption capacity of the soil increased even more significantly with the incorporation of winter wheat straw as fresh organic matter. In our short-term experiments, this indicator manifested both in the year of incorporation and in the residual effects in the second and third years. Specifically, in the residual effect from incorporating the grass mixture, water absorption increased by 16.3–20.6%, while from straw, it increased by 22.8–34.6%. This can be explained by the fact that when straw is used as fertilizer, a significantly more significant amount of fresh dry matter is incorporated into the soil, which decomposes over a more extended period and consequently better structures the soil. This has been established by many studies, including our own, conducted significantly earlier [Ovcharuk, 2020a; Ovcharuk, 2020в; Hamaiunova, 1983]. In modern agricultural practices, straw from cereal crops is the cheapest organic fertilizer. It should not be burned, as not only the fresh organic biomass is destroyed, but also the organic matter that has formed over the years in the topsoil. Moreover, this approach significantly weakens the soil's microbiological activity and pollutes the air with CO_2. Like manure, incorporating straw into the soil positively influences microbiota development (Table 4).

As the data presented indicates, with the incorporation of organic matter into the soil, the abundance of the studied types of microorganisms, especially cellulolytic ones, increases, while in the case of straw burning, it significantly decreases even compared to unfertilized soil. Therefore, fresh organic plant biomass should not be burned; it should be incorporated into the soil to structure it, enhance microbiological activity, and enrich it with organic matter, humus, nutrients, trace elements, etc. The use of straw as fertilizer does not require significant costs. However, it is low in nitrogen and has a relatively high C:N ratio, so it is necessary to apply nitrogen fertilizers simultaneously with its incorporation to accelerate straw decomposition. An effective measure is to sow a grass mixture with a legume component immediately after harvesting the cereal crop. Even in years unfavorable for moisture, an average of 20–25 tons/ha of fresh, moist organic matter is formed in the field, resulting in biological nitrogen production. The decomposition of straw and green grass mixtures is accelerated, reducing nitrogen requirements.

Of course, perennial leguminous grasses can accumulate the most nitrogen due to their symbiotic activity. According to our research, after three years of growing alfalfa, the soil is enriched with an average of 30 tons of organic matter and about 200 kg/ha of biological nitrogen [Hamaiunova et al., 2023]. This nitrogen is ecological, free of charge, and is utilized 100% by subsequent crops over several years without losses or harmful effects on product quality and the environment. The deep penetration of the root system and its spread in the soil ensure the highest water filtration rate—up to 0.94 mm/min. For example, in a second-year alfalfa crop, up to 115.0 mm of water is absorbed within the first hour and more than 60.0 mm by the fourth hour.

As is known, alfalfa cultivation is an essential element of agricultural production, especially in the context of animal husbandry. Alfalfa (Medicago sativa) is a valuable forage crop that provides high productivity and nutritional quality for livestock. However, without animal

Table 4. The content of specific types of microorganisms depending on the application of organic fertilizers (average for 2021–2023)

Experimental variant	Ammonifying, million/g		Cellulolytic, thousand/g		Actinomycetes, million/g	
	1	2	1	2	1	2
Without fertilizers	18.98	14.84	2.60	2.61	3.08	3.95
Manure, 60 t/ha	24.22	12.45	3.26	2.33	3.10	3.38
Straw, 6 t/ha	22.53	26.23	2.61	3.27	3.46	4.32
Straw, 6 t/ha (burning)	20.81	10.90	2.01	1.97	3.31	3.36

Note: 1 – ten days after incorporating organic fertilizers (straw and manure into the soil); 2 – after harvesting the grass mixture that was sown after the winter wheat harvest.

husbandry, the need for alfalfa cultivation may decrease. In such conditions, it is advisable to consider alternative annual legume crops that may be more practical and effective.

CONCLUSIONS

Research has highlighted the importance of a comprehensive approach to soil fertility management, including regular application of mineral fertilizers and monitoring physical soil properties to ensure sustainable agricultural development. It has been established that the bulk and specific density of soil composition increases in irrigated soils, indicating the need to monitor these indicators to maintain optimal conditions for plant growth. Incorporating semi-rotted manure and other types of organic fertilizers improves all indicators of soil fertility. Specifically, water-stable aggregates increased to 35.2–38.2%, indicating improved soil structure. The use of organic fertilizers, especially straw, significantly enhances the water absorption capacity of the soil. This is critically important in increasing aridity and ensuring better moisture retention. Incorporating organic matter into the soil promotes microbiota development, particularly cellulose-decomposing microorganisms. This underscores the importance of applying organic matter to maintain soil fertility. Burning straw negatively affects soil fertility and microbial activity. It is recommended that straw be incorporated into the soil to improve its structure and enrich it with organic matter. For effective use of straw as fertilizer, it is advisable to simultaneously apply nitrogen fertilizers and sow grass mixtures with legumes, which contribute to improving soil quality and increasing its fertility.

Perennial leguminous grasses, particularly alfalfa, can significantly enrich the soil with biological nitrogen, an essential factor for enhancing soil fertility. Our research has determined that over three years of alfalfa cultivation, the soil is enriched with an average of 200 kg/ha of biological nitrogen. Alfalfa cultivation also ensures the accumulation of a significant amount of organic matter (about 30 tons), which contributes to improving soil structure and fertility. The alfalfa's deep root system provides a high water filtration rate, which is extremely important for moisture retention in the soil. This is particularly relevant in the context of climate change and increasing aridity. The cultivation of annual legume crops has been proposed as they may be practical and effective under current conditions. This highlights the need to adapt technological elements to changing economic and environmental conditions. Using alfalfa and other leguminous crops has the potential for sustainable agricultural development, providing ecological benefits without compromising product quality and the environment.

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