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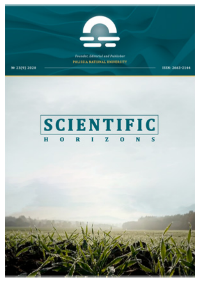

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The role of restoring degraded soils in ensuring food security in the agro-industrial sector

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Abstract. The study was devoted to the analysis of the state of degraded soils in Ukraine, their impact on agricultural productivity and identification of effective approaches to land restoration to ensure food security. The study used a comprehensive approach, including analysis of scientific and official sources, cartographic assessment of the spatial distribution of degraded land, economic assessment of yield losses using

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equations, and research on innovative methods of soil restoration, such as biochar, mulching, and microbiological fertilisers. The results were modelled in Excel, which allowed assessing the impact of innovations on the productivity and profitability of farms. The results showed that more than 40% of arable land in Ukraine is in a state of degradation: water erosion affects 25-30% of the area, most of all in the northern and western regions, wind erosion covers 10-15% in the steppe zone, and humus losses are recorded on 35% of the land, especially in the central part. Heavy metal contamination in industrial regions makes some soils unusable. The economic consequences of degradation include a decrease in wheat, corn, and sunflower yields by 20-30%, an increase in fertiliser costs to UAH 1,800 per hectare, and total losses reaching UAH 15 billion annually. Innovative approaches to restoration, such as biochar, mulching, green manure, and microbiological fertilisers, have shown high efficiency, providing an increase in yields by 15-25% in the first five years, reducing the use of chemical fertilisers by 15-30%, and significantly improving the ecological state of the land. The use of biochar in areas of organic matter deficiency allowed increasing humus by up to 12%, while mulching reduced moisture loss by 20%, making irrigation more efficient. Microbiological fertilisers have significantly reduced the level of soil pollution. The results obtained confirm that the introduction of regionally adapted recovery methods helps to reduce degradation processes and stabilise agroecosystems. This creates the basis for ensuring food security in Ukraine. The study also focused on the need to improve monitoring systems for rapid detection of degraded areas and the development of long-term soil resource management strategies

Keywords: land resources; humus; fertile layer; agricultural production; green manure; mulching

INTRODUCTION

The problem of soil degradation has become one of the most acute environmental and economic challenges for Ukraine, especially given the importance of agricultural production for the national economy. As a result of long-term intensive use of arable land without proper restoration, including erosion processes, humus loss, salinisation, and heavy metal pollution, a significant part of the soil has lost its fertility. During 2014-2024, the area of degraded land was steadily growing, which posed a threat to ensuring food security of the state. The significance of this problem was emphasised by A.O. Gorgots (2023), who analysed the structural components of land use restoration systems in Ukraine. The researcher pointed out the critical need to introduce effective soil restoration mechanisms to support the sustainable development of the agro-industrial complex. A similar emphasis was placed in the study by O.V. Voitseshchuk (2024), who highlighted the scientific and methodological foundations for the rational use of agricultural land, noting that the decline in soil fertility, combined with erosion processes, is becoming a major obstacle to the economic growth of the agricultural sector. One of the key problems in this area remains the loss of humus. A decrease in the natural supply of humus leads to a reduction in the biological productivity of land, which creates additional challenges for farmers and deepens the environmental problems of the regions (Melnychenko, 2024). The critical condition of Ukrainian soils was also the subject of monitoring studies conducted by S.V. Vitvitskyi *et al.* (2019). Monitoring revealed regional features of soil degradation: the most serious were erosion processes in the areas of Donbas and in the strip along the border of the Forest-Steppe with the Northern Steppe. The researchers emphasised the importance of integrated approaches to soil quality monitoring, which should be the basis for management decisions.

Research by V.F. Petrychenko *et al.* (1970) detailed the causal relationships between soil degradation and desertification. They identified several key factors: climate change, organic carbon scarcity, and anthropogenic pressure. The researchers emphasised the need to implement specialised programmes to combat desertification, which should be based on advanced scientific achievements. E. Berezhniak *et al.* (2022) noted that soil degradation is one of the most serious environmental problems in Ukraine, covering more than 40% of arable land that is subject to water erosion, humus loss, salinisation, and chemical pollution. The consequences of this process affect not only agricultural productivity, but also the state of the environment, disrupting the ecosystem balance and reducing the quality of water and soil resources. C.S. Ferreira *et al.* (2022) focused on soil degradation in the Mediterranean regions of Europe, where erosion and loss of organic matter significantly limit agricultural potential. The researchers emphasised that for successful recovery, it is necessary to consider regional climatic and socio-economic features. Their studies are also relevant for Ukraine, as its steppe regions are similar in characteristics to the Mediterranean zones and also suffer from droughts and wind erosion.

Analysis of current approaches to soil restoration conducted by J. Wang *et al.* (2023), demonstrated that remote sensing technologies can effectively detect critical degradation zones, creating the basis for implementing point-based measures. The research emphasised the importance of regular monitoring using satellites, which allows observing the dynamics of changes and quickly assessing the effectiveness of the implemented methods. Another important aspect is the relationship between soil degradation and food security. The study by P.M. Kopittke *et al*. (2019) examined increasing agricultural intensity in the face of growing food demand: the researchers emphasised that without a balanced approach, intensification can lead to irreparable soil degradation, reduced fertility, and reduced access to agricultural land for future generations. At the European level, research by P. Pereira *et al*. (2023) detailed the impact of agricultural practices on soil health, noting that poor resource management accelerates desertification and humus loss. They emphasised the need to review traditional land use methods and introduce innovative solutions adapted to local conditions.

Although there is a significant body of research on this topic, gaps remain in the economic rationale for soil restoration measures and the long-term impact of their implementation on food security. Research mainly focused on individual aspects of degradation (structural, chemical, environmental), but there was no comprehensive approach that would consider the regional specifics of the problem, financial costs, and potential productivity gains in the implementation of innovative technologies. The purpose of the study was to determine the economic feasibility and environmental effectiveness of modern methods of restoring degraded soils in the context of strengthening food security in Ukraine. Special attention was paid to the assessment of regional differences and the integration of innovative solutions that can increase the efficiency of agricultural production and contribute to environmental stability.

MATERIALS AND METHODS

The study was based on the analysis of scientific papers, government programmes, regulatory documents, and statistical data. The sample data included an assessment of soil conditions in agricultural regions of Ukraine that had a high level of degradation. The review included official data from the State Statistics Service of Ukraine, the Food and Agriculture Organisation (FAO) database (2025). Data from regional reports of agricultural farms and recommendations of agronomic centres were also analysed (Gusarova, 2024; Ukrainian development for…, 2024). The research process was based on an integrated approach to analysing the spatial distribution of degraded land. The main tool was the analysis of maps of degraded soils, namely, their territorial distribution (Soil erosion in Ukraine, 2025). This helped to identify critical areas and assess the scale of the problem. A qualitative assessment of each of the degradation zones was carried out based on cartographic models. This helped to identify critical zones that have the greatest impact on the productivity of the agro-industrial complex. Special attention was paid to areas with high intensity of water erosion (northern part of Kyiv Oblast and western part of Cherkasy Oblast), and zones with a lack of organic matter due to long-term agricultural turnover (Forest-Steppe and Steppe zones).

The economic aspects of soil degradation were estimated by calculating losses caused by reduced yields of major agricultural crops such as wheat, corn, and sunflower for the period 2021-2024. The methodology was based on comparing the average yield indicators on degraded land plots with similar indicators for land in proper agroecological condition. For this purpose, official statistics of the State Statistics Service (Statistics Ukraine "Plant Growing in Ukraine", 2022) were used. Key indicators of food security were analysed to assess the impact of soil degradation on ecosystems, agriculture, and populations. Key indicators included food availability, public accessibility, food quality, and supply stability. Food availability is an estimate of the output of major agricultural crops, such as wheat, corn, and sunflower. Accessibility to the population was determined by analysing the impact of changes in yields on food prices in regions experiencing soil degradation. The stability of supply was also evaluated – the dynamics of yield and its fluctuations under the influence of degradation factors, such as erosion, salinisation, and loss of humus.

The economic analysis of losses caused by soil degradation was carried out based on comparing the yields of major agricultural crops, such as wheat, corn and sunflower, on degraded land and land in proper agroecological condition. Land in proper condition was determined according to the following criteria: humus content of more than 3%, stable water retention capacity, no signs of erosion, salinity, or chemical contamination. Data on soil yield and quality characteristics were collected from official sources, such as statistical collections (Statistics Ukraine "Plant Growing in Ukraine", 2022), and regional reports of agricultural enterprises and databases of the State Statistics Service (Ukrainian development for…, 2024; The State Statistics Service summed up…, 2024). The calculation of losses was carried out in two key stages: determining the loss in yield and monetising these losses. The yield loss was calculated using the equation (1):

$$\Delta Y = Y_s - Y_d, \tag{1}$$

where Y_s – average yield on healthy land for 2021-2024 (t/ha); Y_d – yield on degraded land (t/ha); ΔY – difference between them.

The second stage involved monetisation of losses. Economic losses (L) were calculated using the equation (2):

$$L = \Delta Y \times P_c \times A, \tag{2}$$

where P_c – average market price for products (UAH/tonne); A – area of degraded land (ha). Purchase prices are based on the average annual performance of "Nibulon" for the period 2021-2024. This company was chosen as a source for price indicators due to its leadership in the grain market in Ukraine, which guarantees the representativeness of the data obtained. The company also occupies a leading position in the production and export of agricultural products, and its purchase prices are used as indicator prices in the market (Purchase prices, 2025). For greater accuracy, the monetisation process (Equation 2) also considered indirect costs caused by increased costs for nitrogen and potash fertilisers, soil preparation and irrigation, which become necessary due to the loss of humus and deterioration of the physical and chemical properties of the soil.

Land in proper agroecological condition was characterised by the following indicators: humus content of more than 3% and the absence of physical signs of erosion; optimal chemical parameters: soil pH in the range of 5.5-7.5; stable yield over the past three years, which had a deviation of 10% from the average annual level. The humus content and pH of the soil are indicated as reference parameters for chernozems of the Forest-Steppe and Steppe zones. For other soil types, these indicators can be adjusted depending on the natural conditions of the region and soil and agrochemical characteristics. The approach based on the application of equations (1) and (2) allowed conducting a detailed analysis of losses for each crop separately and obtaining an overall picture of degradation risks, which will contribute to the development of effective regional strategies for soil restoration.

In the process of analysing innovative approaches, several technologies were considered, in particular biochar (carbon-containing material produced by pyrolysis of organic waste); green manure (plants that are grown to improve the soil and increase its organic mass); mulching (a method that consists in covering the soil surface with a protective layer of plant material or special organic coatings); microbiological fertilisers (a complex of beneficial bacteria that stimulate plant growth and improve the absorption of nutrients from the soil). The effectiveness of each method was evaluated using a comparative cost-benefit analysis.

The efficiency assessment methodology was based on a comparison of regions where the main degradation factors clearly correspond to certain innovative methods (Poltava, Vinnytsia, Kherson, Dnipropetrovsk oblasts). This helped to determine the most economically substantiated solutions for implementation in degraded territories, considering their regional characteristics. The method of predicting the increase in soil yields based on the analysis of the results of the application of such technologies as biochar, green manure, mulching, and microbiological fertilisers was also used. The data of current studies were extrapolated and yield growth was predicted in the form of expected changes in productivity indicators for 3-5 years based on the results obtained considering the applied innovative approaches to soil restoration. To determine the impact of recovery methods on farm productivity, modelling was performed using Excel software suite. The results were based on the integration of a systematic approach to data selection, and qualitative analysis of modern technologies. Thus, the study creates a theoretical platform for further implementation of innovative approaches in the practice of the Ukrainian agro-industrial complex.

RESULTS

The link between soil degradation and food security is important, as soil degradation has a direct impact on agricultural productivity and the availability of basic food products for the population. Reduced soil fertility due to erosion, pollution, or depletion of natural resources leads to reduced crop yields. This creates not only economic difficulties for farmers, but also contributes to higher food prices. As a result, especially in the face of climate change and unstable weather conditions, countries facing soil degradation are becoming less able to meet domestic food demand, increasing their dependence on food imports, increasing food security risks. In addition, soil degradation not only reduces yields, but also increases the cost of agrotechnical measures. Due to the loss of land fertility, farmers are forced to use additional fertilisers and irrigation systems to support production, which, in turn, increases the cost of production. This increase in spending may make food less accessible to the general population, especially in countries where agriculture is the main sector of the economy. Moreover, additional economic pressures can lead to a decrease in the financial availability of agricultural products, which significantly complicates the situation with food security and health of the population, because worse economic opportunities force some of the population to choose cheaper, often low-quality products.

Thus, the relationship between soil degradation and food security not only highlights the need for government initiatives to combat soil degradation, but also serves as an important guideline for soil resource recovery strategies. Restoring soil fertility through the use of environmentally sustainable agricultural production methods is one of the key factors for ensuring food security in the context of global economic instability. It can also help reduce dependence on food imports, which, in turn, will ensure the stability of food production and availability in the domestic market, and increase the resilience of rural communities to climate change and extreme weather events.

Assessment of the level of soil degradation in Ukraine. The study showed that soil degradation is a critical environmental problem for the agricultural complex of Ukraine. Analysis of data from various sources, including the State Statistics Service of Ukraine and the FAO database (2025), shows that more than 40% of arable land is in a state of degradation, including erosion, humus depletion, salinisation, and pollution. Water erosion is one of the key problems of degraded land in Ukraine, especially common in the western, northern, and central regions (Pichura *et al.*, 2024). This problem primarily affects the western and northern regions (Polissia and Forest-Steppe zones), and the central part of the country. According to available data, water erosion in Ukraine covers 13.4 million hectares of land, of which 10.6 million hectares are arable land. Among them, 4.5 million hectares suffered moderate or severe degradation, and 68 thousand hectares completely lost the humus horizon. These consequences arose from the long-term environmentally unjustified exploitation of land resources and excessive ploughing of soils (Berezhniak *et al.*, 2022). Wind erosion accounts for 10-15% of all affected areas (Gusarova, 2024). The main cause of wind erosion is the lack of forest belts and intensive tillage. It is most common in the Southern Steppe regions, including Kherson and Mykolaiv oblasts, where wind storms annually carry up to 30 tonnes of soil per hectare. Humus loss is a problem about a third of soils, especially in the central and southern regions, are characterised by a low content of organic matter. In many areas, the humus content has dropped to below 2%, which critically affects soil fertility. The greatest losses of humus are observed in regions with long-term intensive agricultural use, such as the Kirovohrad Oblast.

Soil salinity is observed in steppe regions where irrigation systems are used without proper drainage. This causes the accumulation of salts on the soil surface, reducing its productivity and increasing degradation processes. Along with physical degradation, industrial regions such as Donetsk and Dnipropetrovsk oblasts experience soil contamination with heavy metals, radionuclides, and chemicals. These problems exacerbate the environmental situation and limit the suitability of soils for agricultural production. FAO (2025) data confirm that Kherson, Mykolaiv, and Kirovohrad oblasts are among the areas with the highest level of land degradation in Ukraine, where complex degradation is felt due to humus loss, water erosion, and drought. Cherkasy Oblast has a high level of water erosion due to its location in watersheds and clay soil structure. In the western regions of Ukraine, karst processes and intensive agriculture cause the loss of fertile layers (Table 1).

***Table 1**. Types of soil degradation in Ukraine and their share as of 2024*

Type of soil degradation	% of arable land area (32 million hectares)
Loss of humus and nutrients	43%
Over-compaction	39%
Siltation and crusting	38%
Surface water erosion	17%
Acidification	14%
Waterlogging	14%
Radionuclide contamination	11.1%
Wind erosion, loss of topsoil	11%
Contamination with pesticides and other organic substances	9.3%
Heavy metal contamination	8%
Salinisation, alkalinisation	4.1%
Water erosion, ravine formation	3%
Side effect of water erosion (siltation of water bodies, etc.)	3%
Reduction of the level of daytime surface	0.35%
Deformation of the earth's surface by wind	0.35%
Operation of drained peatlands	0.30%
Aridisation	0.21%

***Source:** created by the authors based on A. Gusarova (2024)*

During the study, it was found that soil degradation not only reduces fertility, but also leads to a deterioration in the quality of water resources due to soil flushing into river basins. Another important consequence of degradation is a decrease in biodiversity due to the loss of natural habitat, and an increase in the vulnerability of agricultural systems to climate change, such as droughts and heavy rains. Analysis of available cartographic materials and data from open sources helped to assess the current state of soil degradation in different regions of Ukraine. The study included thematic maps (Soil erosion in Ukraine, 2025), and reports from international organisations such as FAO (2025).

Water erosion is the main problem of the northern part of the Kyiv Oblast, in particular, the territories adjacent to the Dybynets reservoir. These areas are characterised by a complex terrain with numerous water breaks and slopes, where a significant part of the upper soil layer is washed away due to intense downpours. This reduces the productivity of arable land and creates additional risks for aquatic ecosystems where washed-out soil enters (Environmental passport of the Kyiv region, 2022). On arable land in the central regions, such as the Poltava and Kirovohrad oblasts, there is a decrease in humus content. In these regions, its level has decreased to values that are lower than optimal for ensuring stable yields by 1.5-2%. The main reasons for this degradation are the intensive use of soils in agriculture without proper use of organic fertilisers and green manure. Existing maps and reports indicate that the soils most affected by pollution are located in the industrial regions of Dnipropetrovsk, Zaporizhzhia, Luhansk and Donetsk oblasts (Gusarova, 2024). Exceeding the maximum permissible concentrations of heavy metals (lead, cadmium, mercury) in these zones is caused by the activities of metallurgical plants, mines, and chemical enterprises. This makes these soils unsuitable for agricultural use without special remediation measures. Soil degradation in Ukraine has a pronounced regional specificity due to both natural factors and anthropogenic impact (Fig. 1).

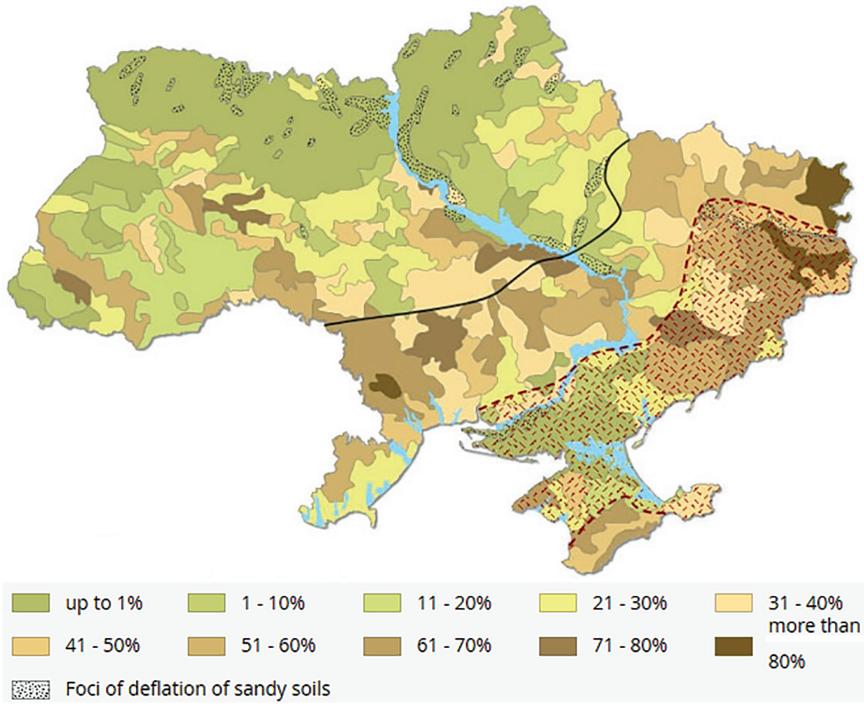

Figure 1. *Degree of soil erosion in Ukraine*
Source: *created by the authors based on Soil erosion in Ukraine (2025)*

This heterogeneity requires the development of individual soil restoration strategies that consider the local characteristics of each region, which directly affects food security. Special attention should be paid to integrated approaches that simultaneously reduce erosion, increase the content of organic substances in soils and reduce the level of pollution, which, in turn, ensures stable and sustainable agricultural production. This approach is important for maintaining soil fertility and contributes to crop growth, which directly affects the provision of food security of the population.

Economic consequences of soil degradation. Due to the gradual depletion of fertile land, the productivity of the main crops, such as wheat, corn, and sunflower, decreases in the range of 20-30%. This decrease in yield is primarily conditioned by the deterioration of the quality composition of soils, in particular, due to the loss of humus, increased erosion processes, and pollution. In addition to directly affecting productivity, soil degradation provokes an increase in production costs, which increase by an average of 15-20%. The cost of fertilisers, especially nitrogen and potash fertilisers, increases significantly, as the natural ability of the soil to provide crops with nutrients decreases (Zymaroieva *et al.,* 2021). It also becomes necessary to introduce special agrotechnical measures, such as deep tillage or covering with organic materials, to improve the structure of the land. Reducing the water retention capacity of the soil creates additional irrigation costs, which significantly increases the cost of growing crops in the arid regions of Southern Ukraine (Mykolaiv, Kherson, Zaporizhzhia oblasts) (FAO Soils Portal, 2025).

The study found that wheat suffers the greatest losses due to the high dependence of its yield on soil conditions. The crop is characterised by a 25% decrease in productivity in regions with degraded soils, accompanied by a 20% increase in growing costs, the total losses for which are estimated at UAH 4 billion. Similar trends are observed for corn and sunflower, with total losses reaching UAH 3 and 2.5 billion, respectively.

Calculations using equation (1) showed yield losses for the main agricultural crops on degraded land compared to land in proper agroecological condition (Table 2). According to the calculations of equation (2), the economic losses for each crop were determined by the average market prices and areas of degraded land.

Table 2*. Calculation of yield losses and monetisation of losses (2021-2024)*

Crop	Yield on healthy land (t/ha)	Yield on degraded land (t/ha)	Yield loss (ΔY) (t/ha)	Average market price (UAH/ tonne)	Area of degraded land (ha)	Economic losses (UAH)
Wheat	4.5	3.2	1.3	6,500	1,000	8,450,000
Corn	6.8	4.9	1.9	5,200	1,500	14,820,000

Source: *created by the authors based on Statistics Ukraine "Plant Growing in Ukraine" (2022), The State Statistics Service summed up the results of the 2023 harvest (2024), Purchase prices (2025)*

During the monetisation process, the costs of improving the physical and chemical properties of the soil were also considered. This includes costs (fertilisers, irrigation, soil preparation) for wheat, corn, and sunflower. The increase in the cost of nitrogen and potash fertilisers accounts for approximately 30% of total production costs, considering the loss of soil fertility. In particular, additional costs for fertilisers for corn amount to 20,000 UAH/ha, thus, for corn on degraded lands, additional costs amount to:

$$1500 \text{ ha} \times 20\,000 \text{ UAH/ha} = 30\,000\,000 \text{ UAH}.$$

In general, considering both direct and indirect costs, the total economic losses due to soil degradation for the regions can reach UAH 61,950,000. Thus, soil degradation leads to significant economic losses, which reduces the economic efficiency of agricultural production. Calculations show that only due to the loss of yield and increased costs for agrotechnical measures, the region can lose up to UAH 62 million annually. Such data are the basis for developing effective measures to restore soils and improve agronomic practices in regions affected by degradation. Economic losses from soil degradation in Ukraine are estimated under the condition of stable prices for agricultural crops and the absence of changes in agrotechnical practices. It was considered that soil degradation occurs at a standard rate, without significant changes in land cultivation technologies or investments in renewable methods. However, if the latest agronomic technologies are implemented in the future and the level of investment in soil restoration increases, economic losses may significantly decrease. The model does not consider the impact of inflation, changes in energy prices, or global climate changes that may have a significant impact on the situation in the future.

In addition, based on calculations (Table 2), economic losses from soil degradation amount to up to UAH 15 billion per year. However, these calculations assume that there are no significant changes in current agronomic practices and the effectiveness of state measures to restore degraded land. Considering possible unexpected factors, such as catastrophic climate change or potentially new methods of soil regeneration, these losses can both decrease and increase depending on further changes in the economy and agrotechnological sphere of Ukraine. Soil degradation also has larger economic consequences. Reducing the profitability of agricultural enterprises increases the cost of production, reducing the competitiveness of Ukrainian exports on world markets. A long-term decline in productivity threatens a significant decline in export volumes, which make up a significant share of the national economy. The social consequences are manifested in a decrease in employment in the agricultural sector and a decrease in the income of the rural population, which increases the vulnerability of certain groups of the population. Soil degradation leads to significant economic losses, which can threaten Ukraine's food security without timely intervention.

Effectiveness of innovative methods of soil restoration. The results of the study show that innovative methods adapted to the specifics of regions and types of soil degradation demonstrate high efficiency in restoring soil fertility and increasing their productivity. Several approaches applied in different natural and climatic zones of Ukraine are evaluated. The use of biochar in the regions under study significantly improved soil quality, especially in areas with a lack of organic substances, such as Forest-Steppe and parts of the Steppe. This method has shown high efficiency in regions where erosion has led to a loss of humus and a decrease in the water retention capacity of the soil. Three years after the introduction of biochar, the humus content increased to 12%, which became the basis for an increase in yield by 15-20% (Gorgots, 2023). Due to the reduction in the need for mineral fertilisers by 10%, the cost per hectare decreased by about UAH 800, which made this method economically profitable. Biochar showed the best results in the zone of the Poltava Oblast, where soil degradation is caused by intensive land use.

Sideration as a method of soil refinement proved to be effective in Forest-Steppe zones, where the level of organic matter is reduced due to long-term agricultural use (Zorin, 2024). Sowing green manure, especially legumes such as lupine and clover, increased the organic layer, improved soil structure and increased yields by 10% after two years. The use of green manure has reduced the use of nitrogen fertilisers by 30%, which has had a positive impact on the production economy and the ecological state of the region (Gorgots, 2023). The technique showed the greatest effectiveness in the Vinnytsia Oblast, where water erosion and humus losses are particularly common.

Mulching has proven effective in arid regions of Southern Ukraine, such as the Kherson Oblast, where wind erosion significantly complicates agriculture. Applying mulch to the soil surface reduced moisture loss due to evaporation by 20%, making irrigation more efficient and yields increased by 8-12% at no additional cost. Mulching also helped to reduce erosion processes by creating a protective layer that prevented soil loss (Onopriienko *et al.*, 2023). The method is well adapted for areas with low levels of organic matter, where other technologies have proven less effective. In regions with high heavy metal contamination, such as Dnipropetrovsk Oblast, the use of microbiological fertilisers has helped to activate phytoremediation processes and improve soil structure, reduce erosion, and maintain fertility. The introduction of biologics allowed increasing the yield by up to 25%, while reducing the use of chemical fertilisers by 15-20% (Ukrainian development for..., 2024). This method helps to increase natural soil fertility and reduce ecosystem pollution. Official data of the State Statistics Service of Ukraine and the FAO database for 2021-2024 were used to analyse the effectiveness of implementing innovative methods in soil restoration. The information covers generalised yield statistics, dynamics of degradation processes on arable land, and economic indicators such as additional income, cost reduction, and net profit (Table 3).

***Table 3**. Successful implementation of innovative methods of soil restoration (2021-2024)*

Method	Area	Year	Moisture loss (%)	Increase in yield (%)	Additional income (UAH/ha)	Cost reduction (UAH/ha)	Net profit (UAH/ha)
Biochar	Poltava	2021	-	+10	3,000	500	3,500
		2022	-	+12	3,600	600	4,200
		2023	-	+15	4,500	750	5,250
		2024	-	+18	5,400	900	6,300
Green manure	Vinnytsia	2020	-	+8	2,400	400	2,800
		2021	-	+10	3,000	500	3,500
		2022	-	+12	3,600	600	4,200
		2023	-	+14	4,200	700	4,900
		2024	-	+15	4,500	750	5,250
Mulching	Kherson	2020	-15	+5	1,500	300	1,800
		2021	-18	+7	2,100	420	2,520
		2022	-20	+9	2,700	540	3,240
		2023	-22	+10	3,000	600	3,600
		2024	-25	+12	3,600	720	4,320
Microbiological fertilisers	Dnipropetrovsk	2021	-	+12	3,600	600	4,200
		2022	-	+15	4,500	750	5,250
		2023	-	+18	5,400	900	6,300
		2024	-	+20	6,000	1,000	7,000

Source: *created by the authors based on FAO Soils Portal (2025)*

The areas shown in Table 3 were selected to evaluate the effectiveness of innovative methods due to their representativeness and different types of degradation problems. Each area is characterised by certain problems associated with soil degradation, which corresponds to the conditions for applying the appropriate method. The Poltava Oblast was chosen because of the decrease in humus content in soils, which is characteristic of intensive land use. The use of biochar has significantly improved productivity indicators: already in 2021, the yield increased by 10%, reaching 18% in 2024. Net profit increased to UAH 6,300/ha due to lower fertiliser costs and increased yields. Sideration is used to increase the organic mass and reduce the impact of erosion common in the Forest-Steppe zone (Vinnytsia Oblast). The results showed an increase in yield from 8% in 2020 to 15% in 2024, which provided a net profit of UAH 5,250/ha. Reducing the cost of nitrogen fertilisers (by 30%) has made the method economically attractive for long-term implementation.

The southern regions of Ukraine, in particular, the Kherson Oblast, are characterised by wind erosion and high moisture losses. Mulching showed a steady reduction in moisture loss by up to 25% and a 12% increase in yield in 2024. Net profit increased to UAH 4,320/ha due to optimisation of irrigation and reduction of irrigation costs. Dnipropetrovsk Oblast was chosen because of the high level of heavy metal pollution, where microbiological fertilisers effectively restore the structure of soils and enhance their fertility. From 2021 to 2024, the yield increase reached 20%, and net profit increased to UAH 7,000/ha. Regional results showed that in the arid zones of the southern region (Kherson and Mykolaiv oblasts), mulching and biochar helped to compensate for losses due to erosion processes, and maintain productivity even in adverse weather conditions. In the Polissia area, where water erosion is the main threat, significant results have been achieved due to the introduction of anti-erosion technologies. The use of water management technologies, such as the design of terraces and irrigation systems, has improved soil moisture retention by 18-25% in regions with reduced precipitation.

According to the forecasts made based on extrapolation of the above data, the use of biochar, sideration, mulching, and microbiological fertilisers will contribute to increasing yields in different regions of Ukraine over the next 3-5 years (Fig. 2). It is expected that the introduction of these technologies will provide significant improvements in soil productivity, in particular, reducing erosion and increasing moisture retention, which will have a positive impact on the economic results of the agricultural sector.

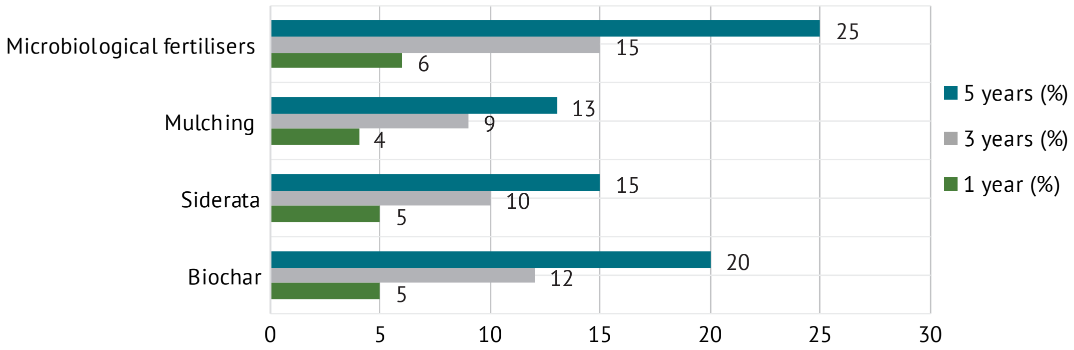

***Figure 2**. Potential yield growth depending on recovery methods*
***Note:** as a percentage of yield growth relative to degraded land*
***Source:** created by the authors*

The graph shows that the highest yield increase is predicted when using microbiological fertilisers, while the use of biochar implies a stable long-term increase in productivity. Green manure and mulching will provide gradual and even growth in the longer term. The data confirm that the choice of soil restoration method depends on the specific type of degradation, which highlights the importance of a differentiated approach to each situation to preserve food security. Biochar is optimal in regions with a low humus content, which helps to maintain soil fertility and increase agricultural production. Green manure is effective in areas with structural disorders of the soil, where its use helps to restore the physical characteristics of soils and ensures the stability of yields. Mulching is effectively applied in the face of wind erosion, reducing water loss and increasing crop resistance to drought, which is key to ensuring sustainable food production. Microbiological preparations are used in areas with chemical contamination, helping to clean soils of toxic compounds and restore their natural fertility. These innovative methods of soil restoration not only increase the productivity of the agricultural sector, but also reduce environmental risks, thereby making a significant contribution to stable food supplies, which is an important aspect of Ukraine's food security.

Comprehensive assessment of the impact of soil restoration on food security. The analysis of the conducted research shows that the introduction of innovative measures to restore degraded soils not only reduces yield losses, but also significantly improves the economic and environmental indicators of agricultural production. The most significant increase is the yield, which varies between 15-25% within the first 3-5 years after the start of using innovative methods. This is ensured by restoring the humus balance, improving water retention capacity, and activating biological processes in the soil. An additional advantage is to reduce dependence on chemical fertilisers by increasing the natural fertility of the soil. This trend significantly contributes to the ecological balance in regions where intensive agriculture has led to pollution of water bodies and increased soil acidity. Reducing fertiliser costs has a direct impact on reducing the cost of growing major crops such as wheat, corn, and sunflower. According to the results of the study, cutting the use of nitrogen fertilisers by 25-30% reduces the cost of each hectare of arable land from UAH 1,500 to 1,800, depending on the crop, soil conditions and region. In regions where the organic matter of soils was restored due to the use of green manure and biochar (Poltava and Vinnytsia oblasts), farmers observed a decrease in the cost of mineral fertilisers by almost a third without reducing yields.

The combination of cost reduction with an increase in yield, which reaches 15-25% in the first three years after the introduction of innovative methods, provides a significant increase in the net profit of farms. For example, if the average annual wheat yield in regions using biochar increases from 3.5 to 4.5 t/ha, and the average grain price is 6,000 UAH/t, this adds 6,000 UAH/ha to the total income while maintaining costs at a minimum level. The study confirms that technologies such as mulching help to reduce moisture evaporation by 20%, which is especially important for the southern and arid regions of Ukraine, in particular, for the Kherson Oblast. This reduces the volume of water used for irrigation, and reduces the cost of electricity or fuel for the operation of irrigation systems. Estimates show that this optimisation reduces irrigation costs to 800 UAH/ha during the growing season. On the scale of a farm, this can mean saving tens of thousands of UAH, especially in large agricultural enterprises.

Technologies for restoring the soil structure through the introduction of biochar and mulching can reduce the need for deep ploughing and loosening. These measures usually require significant costs for fuel and maintenance of equipment. The use of biochar helps to improve the water retention capacity of the soil, which minimises the cost of repeated agrotechnical works, reducing the cost of land cultivation by about 100-200 UAH/ha, depending on the chosen technology. In general, the combined use of innovative methods can reduce production costs by 20-30% in regions with a high level of soil degradation. This contributes to a significant increase in the profitability of farms and increases their economic stability. Reducing direct costs for fertilisers, irrigation, and agrotechnical measures, together with increasing yields, lays the foundation for stable economic development of the agro-industrial sector.

Successful implementation and scaling of innovative approaches to the restoration of degraded soils requires a systematic approach that considers regional characteristics, technical availability, and cost-effectiveness of methods. Large-scale introduction of microbiological fertilisers is recommended in Forest-Steppe and Steppe regions where there is a critically low humus content (1.5-2%). These preparations can effectively activate the biological activity of soils and reduce dependence on mineral fertilisers by 15-20%. Due to the increase in natural fertility, the use of microbiological fertilisers can provide an additional increase in yield at the level of 10-25% after three years of use. In areas with frequent droughts, such as the Kherson and Mykolaiv oblasts, the introduction of mulching should be a priority. By reducing moisture evaporation by 20% and stabilising soil moisture, mulching allows maintaining crop productivity even in adverse climatic conditions. This approach reduces irrigation costs and reduces the need for water resources, which is critical for regions with significant water scarcity. In regions with high erosion activity, such as Vinnytsia and Cherkasy oblasts, large-scale use of green manure is recommended. Sowing legumes such as lupine and clover helps to enrich the soil with organic matter and reduce the risk of erosion. Sowing green manure can improve the soil structure, and their use in crop rotation allows reducing the volume of mineral fertilisers by up to 30%, which reduces agricultural production costs.

Policy measures and state support for innovative methods of restoring degraded soils in Ukraine. For the effective implementation of innovative approaches to the restoration of degraded soils in these regions, state support is needed through the provision of subsidies for the purchase of microbiological fertilisers, green manure and mulching products, and tax incentives for farmers who implement these methods. To reduce the financial burden, it is recommended to introduce co-financing at the level of 30-50% of the cost of technical means and materials necessary for the use of the latest technologies. In addition, the creation of grant programmes can allow farmers to receive irrevocable funds for the introduction of environmentally sustainable practices, such as mulching and the use of green manure.

Conducting pilot programmes in each of the main agricultural regions of Ukraine will allow adapting innovative approaches to local conditions. For example, the USAID Agriculture Resilience Initiative (AGRI) was one of the largest projects that provided funding to support innovations in the agricultural sector of Ukraine. The programme was aimed at increasing agricultural production, in particular, in the context of climate change, through the introduction of the latest technologies and agrotechnical methods. Under the programme, farmers and farmers can receive sub-grants that allow them to invest in innovative equipment, new biologics, and the integration of high-tech methods of soil treatment and irrigation. The programme was being implemented in many regions of the country, especially in areas where soils are experiencing degradation due to a lack of organic matter or unstable access to water resources. Another important step in adapting agricultural land to extreme climatic conditions is the Drought Management Plan in Ukraine, developed to combat the effects of climate change. This plan includes the use of efficient irrigation methods, the use of technologies such as mulching, and the optimisation of water use. In particular, mulching can reduce moisture evaporation by 20% and maintain soil moisture levels even in conditions of prolonged droughts. The introduction of such approaches in the southern regions of Ukraine, in particular in the Kherson, Mykolaiv, and Zaporizhzhia oblasts, can significantly reduce irrigation costs and maintain the sustainability of agricultural land. In addition, the programme provides funding for the implementation of such events, in particular, at the expense of subgrants for farmers, which allows attracting partial state support for such projects.

Special attention in the restoration of degraded land is paid to phytoremediation, which includes the use of specialised biologics for cleaning soils from heavy metals. This technology is an effective way to restore land affected by industrial pollution or contaminated with heavy metals after military operations. For soil cleaning, special plants are often used that absorb toxic substances, enriching the soil with organic materials, and promoting their structural stability. Such programmes are already being implemented in Ukraine in areas where the level of heavy metal pollution is critical, for example, in the Dnipropetrovsk and Kryvyi Rih industrial regions. Expanding these practices will improve the ecological state of contaminated areas and reduce the cost of mechanical or chemical soil cleaning, which is much more profitable in conditions of limited budget resources.

A systematic approach to innovation also implies political support. This may include subsidies for the purchase of environmental fertilisers, funding for agricultural research, and organising training programmes for farmers on innovative soil management techniques. An example of such a program is life HelpSoil, a project funded under the LIFE Programme of the European Union and aimed at supporting sustainable soil management, in particular, through the development and implementation of new strategies to increase soil fertility, improve their physical and chemical properties and, as a result, increase the environmental sustainability of agricultural systems. The project covers many aspects of soil management, such as preserving organic matter in the soil, improving water retention capacity, reducing erosion, and using bioinnovation technologies to improve agricultural efficiency in the face of climate change. An important area is the integration of environmental measures that reduce the burden on the environment, while contributing to economic benefits for farmers, such as reducing the cost of mineral fertilisers through the use of organic and biological soil stimulants.

It is possible to adapt the LIFE HelpSoil programme for Ukraine by implementing similar strategies in the main agricultural regions suffering from soil degradation, such as the Steppe, Forest-Steppe, and southern regions of the country. Ukraine, with its large agricultural territories and agrarian orientation of the economy, could integrate the principles of the programme into its state policy by financing soil restoration projects through subsidy programmes and grants for farmers. For example, support for the use of technologies for restoring organic soil content, such as mulching, the introduction of green manure or organic fertilisers, and the use of biologics to improve soil fertility and reduce the use of chemical fertilisers. There are opportunities to adapt already proven methods to specific conditions in Ukraine, such as reducing the negative impact of droughts and erosion, and increasing the resilience of agricultural farms to climate change.

The development of a national soil restoration programme should become one of the priorities of state policy. This programme should include targeted financial incentives for regions with the highest levels of degradation, such as the southern regions affected by drought and industrial regions exposed to heavy pollution. The programme should provide flexible arrangements for the allocation of funds, considering the specific needs of each region. Consequently, the introduction of innovations contributes to long-term food security, reducing the risks of food shortages and ensuring the stability of agro-industrial production. This was made possible by simultaneously increasing the sustainability of agricultural systems and increasing production volumes that meet the domestic and export needs of Ukraine. It is important to develop long-term plans for natural resource management, including periodic monitoring of soil conditions and the introduction of tools for assessing degradation risks.

DISCUSSION

The results confirm that innovative methods have a significant impact on soil restoration and strengthening food security. Increasing yields, reducing fertiliser costs, and improving the ecological state contribute to the economic stability of the agricultural sector. These approaches also lay a solid foundation for the ecological and social development of regions, creating more sustainable and productive agricultural systems. An assessment of the state of land in Ukraine found that more than 40% of arable areas suffer from various types of degradation, such as erosion, humus loss, salinisation, and pollution. Similar trends were recorded by H. Eswaran *et al.* (2019), who described soil degradation as a global problem that significantly affects land productivity and biological value. Water erosion, which covers 25-30% of the territories, was identified as the main type of degradation in Ukraine. These results are supported by A. Hossain *et al.* (2020), who emphasised that erosion is one of the key causes of fertility loss due to intensive land use and climate change

The decrease in humus content to critical levels (1.5-2%) in the central regions of Ukraine coincides with the conclusions of K. Lorenz *et al.* (2019), who identified organic carbon as a key indicator of soil fertility. The loss of humus in the regions under study correlates with the results of other countries, which confirms the global nature of the problem. K. Lorenz *et al.* also noted that low levels of humus are an obstacle to achieving the sustainable development goals, which focuses on the environmental component of the study. Economic losses caused by soil degradation, in particular, a decrease in yields by 20-30% and an increase in fertiliser costs, reflect the strong negative impact of this process on the agricultural economy. Similar conclusions were drawn by E. Midler (2022), who noted that degradation significantly increases the cost of agricultural production due to rising resource costs. The data obtained in the study on an increase in the cost of nitrogen and potash fertilisers to UAH 1,500-1,800 per hectare confirm this trend.

Innovative restoration methods, including biochar, mulching, and green manure, have been shown to be highly effective in improving land productivity and reducing fertiliser costs. An increase in yield of up to 25% when using microbiological fertilisers correlates with data by M. Baude *et al.* (2019), who proved that ecological approaches can significantly improve land productivity even in adverse conditions. The high efficiency of mulching in drought zones in Ukraine confirms the data obtained by other researchers for arid regions of the world. These studies confirmed that a significant part of the land in Ukraine, in particular, in the steppe regions, is subject to salinity due to incorrect irrigation management. Similar problems were described in detail by I. Kramer and Y. Mau (2020), who applied the SOTE model to assess degradation risks due to salinity in different countries. Their analysis showed that areas affected by salinity reduce soil productivity by more than 25%, which is also confirmed for Ukrainian regions. The identified problem of reducing the level of organic carbon in the soils of Ukraine confirms the trends described by Q. Jin *et al.* (2022). In their research conducted in rice fields in China, it was found that soil degradation leads to a loss of organic carbon and limits the ability of the soil to retain nitrogen and phosphorus. Similar trends in the loss of humus and nutrients were recorded in the Steppe and Forest-Steppe zones of Ukraine, which leads to the need to introduce stabilisation technologies, such as biochar and green manure.

The economic aspects of degradation identified in the study are consistent with the findings of O. Popovych *et al.* (2023), who considered losses from reduced yields in the context of agricultural production. Their calculations show that each reduction in yield by 1% leads to losses of an average of 1.2% of farm profit, which coincides with the established losses of profitability for the main crops in Ukraine due to degradation. The effectiveness of innovative recovery methods reflects the key findings of D. Jinger *et al.* (2023), who emphasised the feasibility of using agroforestry to restore degraded land. It was noted that agroforestry reduces erosion processes and contributes to the preservation of humus. The approach is confirmed for the conditions of Ukraine, where mulching and cover crops reduce the intensity of wind erosion by 20% in the southern regions. The comparison of the effectiveness of different soil restoration methods also coincides with the H. El-Ramady *et al.* (2022), who investigated the role of macroflora and macrofungia in the stabilisation of soil systems. The use of biologically active components facilitates not only soil restoration, but also contributes to the transition to sustainable management, which correlates with the proposed solutions in the Ukrainian context, such as the use of microbiological fertilisers (Drobitko & Alakbarov, 2023).

A significant contribution to the discussion was made by O. Olshanska *et al.* (2022), who examined the impact of soil restoration in the context of food security and bioeconomics development. Their analysis confirms the importance of restoring soil fertility as the main factor for ensuring stable agricultural production. Considering the Ukrainian study, the introduction of renewable technologies, such as biochar and mulching, allowed to increase productivity by 15-25%, which underlines their long-term economic effect. Results of the study by R.S. Guedes *et al.* (2021), who addressed the problems of soil restoration at iron mining sites, confirm the importance of adapting recovery methods to local conditions that include physical, chemical, and biological factors. According to the results obtained, the specifics of soil degradation in Ukraine, such as erosion and reduction of humus content, require the use of complex and localised measures. This approach is consistent with the researchers' findings about the need for differentiated strategies to combat soil degradation.

The study by J. Frouz (2021), which focused on soil recovery after mining, pointed out the importance of using vegetation to cover soils and restore microbiological activity. This is consistent with the results of the current study, which also highlights the role of vegetation and organic matter recovery using techniques such as biochar and mulching. Therefore, it was confirmed that a combination of technological and environmental solutions is an effective way to restore degraded soils. Conclusion of S. Kumar and K. Murugesan (2022) on the use of geothermal systems for soil restoration, which demonstrates the importance of technological approaches in the recovery process, has analogies with the results of the current study, which also states that technologies can be an important element in combating soil degradation, but they must be supplemented by environmental approaches. The study by Y. Xue *et al.* (2022), which examined the environmental risks of soil and water loss due to industrial processes, points to the complex relationship between industrial activity and soil degradation. The results of the study confirmed the importance of comprehensive assessments of environmental and anthropogenic factors for managing recovery processes.

An important aspect was the study by J. Mendoza-Vega *et al.* (2020), who focused on soil restoration by planting native trees in tropical mountain forests, points out the importance of vegetation restoration to improve soil quality. This was also supported by the results of the current study, which recommends the use of suitable vegetation and sustainable agricultural practices to restore degraded soils. One of the most important aspects of the study is the process of soil restoration after intensive use of organic fertilisers, in particular manure. Such approaches have been investigated by S.P. Indraratne *et al.* (2009), who drew attention to the rate of soil recovery after the cessation of long-term manure application in agriculture. The authors of the study found that soil restoration lasts for several years, considering the decrease in the content of organic compounds and the establishment of biological activity in the soil. The results of the current study are consistent with this, as it highlights the importance of giving soil systems time to recover from heavy fertiliser use. They confirm that gradual compensation for reduced humus content and microbiological activity is crucial for long-term soil recovery.

Comparison of results with the study by N. Goutal *et al*. (2012), who analysed the natural recovery of soil volume after compaction of forest soils, provided another important area. The researchers emphasised that recovery after compaction depends on natural processes, such as pore formation and increased biological activity in soils. According to the results of the current study, soil recovery after degradation also requires a comprehensive approach that includes not only physical methods, such as aeration, but also the use of natural processes, such as biological activity, which was confirmed by the study of natural soil systems in different ecosystems. Research by J.D. Bolling and L.R. Walker (2000), who investigated the restoration of vegetation and soil on abandoned roads in arid regions, demonstrated the importance of vegetation's ability to recover from disturbances in preserving soil structure. In this paper, it was demonstrated that successful soil restoration depends on the type of vegetation that can quickly restore the soil structure. This approach is reflected in the current project, which highlights the importance of selecting suitable vegetation to improve soil conditions. In particular, it is important to investigate the interaction between plants and soil for effective restoration of degraded land. The results of the current study, based on which it is possible to recommend the use of natural processes and approaches for soil restoration, are consistent with the conclusions of other researchers. The importance of finding integrated recovery methods that combine technical and natural aspects is a common trend in modern scientific developments, which can become the basis for further research in this area.

CONCLUSIONS

The study confirmed that soil degradation in Ukraine is a multifaceted problem with pronounced environmental, economic, and social consequences. It is estimated that more than 40% of arable land in Ukraine is subject to various forms of degradation, in particular, water and wind erosion. The most affected areas are in Polissia, Forest-Steppe, and in the southern regions of the country, where soil erosion reaches a large scale. In addition, there are problems of humus loss, in particular, in the central and southern regions, where the content of organic substances in many fields is at critical levels, which negatively affects soil fertility. Salinisation and soil pollution due to industrial pollution are also a problem in many agricultural areas.

Analysis of the economic consequences of soil degradation shows that a decrease in the yield of major agricultural crops, such as wheat, corn, and sunflower, leads to significant losses for agricultural enterprises. This is complemented by increased costs for fertilisers and other agrotechnical measures, which creates an additional burden on the budget of farmers, especially in regions with serious degradation problems. Analysis of the effectiveness of innovative methods of soil restoration has shown that these technologies have a positive impact on soil fertility and economic indicators of agricultural production. The use of biochar in the Poltava Oblast led to a significant increase in yields and a reduction in fertiliser costs, which had a positive impact on profitability. Green manure used in the Vinnytsia Oblast showed effectiveness in increasing yields and reducing the use of nitrogen fertilisers, which helped to decrease costs. Mulching in the arid regions of Southern Ukraine has reduced moisture loss and increased yields, which is especially important in conditions of water scarcity. The use of microbiological fertilisers in the Dnipropetrovsk Oblast also contributed to higher yields while reducing fertiliser costs, which provides significant economic benefits. These results confirm the feasibility of implementing such approaches for different types of soil degradation, depending on the specifics of the regions. Further research may focus on integrating remote sensing technologies and creating digital models of soils for operational analysis of their condition. An important area is also the assessment of the long-term impact of innovative methods on the stability of agroecosystems and the economic stability of agricultural production.

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CONFLICT OF INTEREST

None.

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Роль відновлення деградованих ґрунтів у забезпеченні продовольчої безпеки в агропромисловому комплексі

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Анотація. Дослідження присвячено аналізу стану деградованих ґрунтів в Україні, їхньому впливу на продуктивність сільського господарства та визначенню ефективних підходів до відновлення земель для забезпечення продовольчої безпеки. У роботі використано комплексний підхід, включаючи аналіз наукових і офіційних джерел, картографічну оцінку просторового розподілу деградованих земель, економічну оцінку втрат врожайності з використанням формул, а також дослідження інноваційних методів відновлення ґрунтів, таких як біочар, мульчування та мікробіологічні добрива. Результати моделювалися у програмі Excel, що дозволило оцінити вплив інновацій на продуктивність і рентабельність фермерських господарств. Результати показали, що понад 40 % орних земель України перебувають у стані деградації: водна ерозія вражає 25-30 % площ, найбільше у північних і західних регіонах, вітрова ерозія охоплює 10-15 % у степовій зоні, а втрати гумусу зафіксовано на 35 % земель, особливо в центральній частині. Забруднення важкими металами в промислових регіонах робить частину ґрунтів непридатною для використання. Економічні наслідки деградації включають зниження врожайності пшениці, кукурудзи та соняшника на 20-30 %, збільшення витрат на добрива до 1800 гривень на гектар і загальні втрати, що досягають 15 мільярдів гривень щорічно. Інноваційні підходи до відновлення, такі як біочар, мульчування, сидерати й мікробіологічні добрива, показали високу ефективність, забезпечуючи підвищення врожайності на 15-25 % у перші п'ять років, зменшення застосування хімічних добрив на 15-30 % і значне поліпшення екологічного стану земель. Застосування біочару в зонах дефіциту органічних речовин дозволило збільшити гумус до 12 %, тоді як мульчування скоротило втрати вологи на 20 %, зробивши поливи більш ефективними. Мікробіологічні добрива дали змогу значно знизити рівень забруднення ґрунтів. Отримані результати підтверджують, що впровадження регіонально адаптованих методик відновлення сприяє зниженню деградаційних процесів і стабілізації агроекосистем. Це створює основу для забезпечення продовольчої безпеки України. Дослідження також акцентує увагу на необхідності вдосконалення моніторингових систем для оперативного виявлення деградованих територій і розробки довгострокових стратегій управління ґрунтовими ресурсами

Ключові слова: земельні ресурси; гумус; родючий шар; сільськогосподарське виробництво; сидерація; мульчування