SECTION «AGRICULTURAL SCIENCES»

IMPACT OF CLIMATE CHANGE ON DEGRADATION PROCESSES IN SOILS AND WAYS OF THEIR ADAPTATION

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Abstract. *The subject* of the study is the set of cause-and-effect relationships between changes in climatic conditions and the intensification of degradation processes in Ukraine's soil cover, as well as approaches to land-use adaptation aimed at preserving the productive potential of agricultural land. The relevance of the study stems from the fact that soil degradation results from the combined effect of climatic, technological, economic and institutional factors, while current soil conservation practices in Ukraine remain largely fragmented and are further complicated by the consequences of hostilities. *The methodological basis* of the study is a systems approach that treats the soil cover as a component of a single "climate–soil–land use" system, in which a change in one component triggers a response in the others. Analysis and synthesis were used to break down degradation processes into their components and to reconstruct a holistic picture of their interdependence. Scientific generalization was used to systematize the findings of Ukrainian researchers on degradation factors and adaptation directions. Statistical methods and time series analysis were applied to process hydrometeorological observation data and to calculate deviations of actual air temperatures from the 1991–2020 climate normal. The graphical method was used to visualize the identified patterns, comparative analysis to compare arid and humid climate change scenarios and their potential consequences for agroecosystem productivity, and systematization to structure adaptation instruments and their expected

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results. *The aim of the study* is to substantiate a comprehensive model of climate-adapted and environmentally oriented management of Ukraine's soil resources based on an assessment of current climate trends and their impact on soil condition. The empirical basis comprised time series of mean annual air temperature, supplemented by published data on moisture supply and soil temperature. The analysis showed that in 2020–2025 the mean annual temperature never fell below the climate normal, its average for the period exceeded the normal by 1.3 °C, and the maximum was recorded in 2024 (+11.5 °C, a deviation of +2.4 °C). In the Central Forest-Steppe, total moisture input has declined since 1998–2004, resulting in a negative warm-season moisture balance of up to 120–150 mm. Particular attention was paid to soil temperature: according to European studies, soil heat extremes are intensifying faster than air heat extremes, which makes soil temperature a more informative indicator for land-use planning than air temperature alone.

Nine adaptation directions were identified and characterized: regulatory and institutional, monitoring, organizational and land management, technological, agrochemical, environmental, agro-energy, economic, and information and awareness-raising. For each direction, its content, implementation instruments and expected results were defined. The directions were systematized in a summary table showing how legal, spatial, technological and motivational mechanisms complement one another within a single management model. Particular attention was paid to the specific needs of de-occupied and frontline territories, where adaptation measures must be combined with the diagnosis of disturbed land and its return to economic use after demining.

Conclusions. The study shows that slowing down degradation processes requires a shift from isolated soil conservation measures to the integrated implementation of interrelated, interdisciplinary adaptation directions. Their effectiveness is determined not by the sum of individual effects but by the nature of the interconnections between them: scientific justification without institutional consolidation remains a recommendation, and a regulatory requirement without an economic incentive remains a formality. *The results are of practical* value for shaping national policy on the adaptation of the agricultural sector to climate challenges, for preparing land management documentation that takes climate factors into account, and for substantiating

region-specific decisions, including for territories undergoing post-conflict recovery. Future research should focus on the quantitative justification of adaptation measures. *Value/originality.* The study proposes an integrated view of land-use adaptation to climate change in which soil conservation measures are considered not as a set of separate practices but as a system of nine interrelated directions with clearly defined functions, instruments and expected results. Unlike studies that focus on individual agronomic or technological solutions, the proposed model combines regulatory, spatial, technological and motivational mechanisms and places land management documentation at the centre of linking adaptation measures to specific land plots. The study also draws attention to soil temperature as an indicator that is more sensitive to warming than air temperature, and it takes into account the specific needs of Ukraine's territories affected by hostilities, which makes the proposed approach relevant for post-conflict recovery.

INTRODUCTION

Global warming and the associated changes in climate patterns have become major challenges of our time. Soil cover is proving to be particularly vulnerable to these changes. Soil performs fundamental ecological, economic, and social functions. At the same time, it is a natural resource that is non-renewable on the timescale of a human lifetime, as well as the foundation of agricultural production. However, under the influence of global climate change and increasing anthropogenic impact, the soil cover is undergoing increasingly intense degradation processes on both global and national scales.

According to estimates by the Food and Agriculture Organization of the United Nations, more than one-third of the world's soils are in various stages of degradation, and the rate at which this is spreading is rapidly increasing amid climate change. The causes include intensive agricultural practices, deforestation, and climate change. Key manifestations of global warming's impact on soil cover include desertification and erosion, loss of fertility, a decrease in organic carbon content, the thawing of permafrost, and changes in the soil microbiome.

Rising temperatures lead to more frequent and prolonged droughts, causing the soil to lose its structural integrity and become vulnerable to wind and water erosion. Heat stress destroys beneficial soil microorganisms –

the foundation of mineral nutrition for plants – which directly leads to a loss of fertility. Changes in vegetation cover and climate disrupt the soil's ability to accumulate organic carbon, reducing its quality. The thawing of permafrost in Arctic regions causes soil subsidence, disruptions to the hydrological regime, and intense greenhouse gas emissions. Warming also alters the composition of soil microorganisms, which negatively affects crop yields.

Taken together, these processes form a vicious cycle of degradation: a decrease in the organic matter content of soils reduces their carbon sequestration capacity, and the soils themselves become a source of carbon emissions into the atmosphere, which exacerbates global warming; meanwhile, increasing aridity and more frequent extreme weather events, in turn, accelerate the further degradation of the soil cover. From an economic perspective, this means the progressive devaluation of land capital: the land user's lost profits translate into a loss of the territory's natural resource potential. Moreover, the costs of soil restoration, when deferred over time, far exceed the cost of preventive soil conservation measures.

Data from leading international organizations provide clear evidence of the escalating climate crisis. In particular, the 2024 Munich Security Report (MSR) notes that the summer of 2023 set a record for the number of climate-related disasters. This conclusion is supported by data from the World Meteorological Organization (WMO), which stated in its "State of the Global Climate 2023" report that 2023 was the warmest year on record: the average global surface temperature exceeded pre-industrial levels by 1.45°C (± 0.12°C). According to projections presented in the same Munich report, if current trends continue, global temperatures in this century could exceed pre-industrial levels by 2.5–2.9°C, which would have catastrophic consequences for all components of the natural environment, including soil cover [9].

O. Shevchenko, O. Pron and I. Chebotarova consider global warming to be one of the key factors affecting the ecological condition of agricultural land and agroecosystems. The researchers have shown that changes in temperature regime, in the amount and intensity of precipitation, and the increasing frequency of extreme weather events lead to lower crop productivity, changes in the species composition of flora and fauna, soil degradation and deterioration of water resources. They examined degradation

processes that reduce land quality and result in ecological and economic consequences. The authors proposed a set of measures aimed at adapting agroecosystems to climate change, including sustainable management of land and water resources, biodiversity conservation, the introduction of soil conservation technologies and raising public environmental awareness [11].

S. Ivaniuta, O. Kolomiiets, O. Malynovska and L. Yakushenko examined climate change as one of the greatest threats to key sectors of Ukraine's economy and society, including land resources, agriculture, forest and water resources, energy, infrastructure, biodiversity and emergency response. For agriculture, the authors identify moisture conditions as the leading factor limiting production efficiency and the use of the natural potential of farming. They note that droughts in different agroclimatic zones recur with a frequency of 20–40% and have become almost twice as frequent over the last 20 years. The report also highlights uneven regional dynamics: compared with 1990, average grain and legume yields rose by 46–61% in the Forest-Steppe and Polissia but fell by 10% in the Steppe. The researchers analysed international experience of climate change adaptation, assessed the possibilities of applying it in Ukraine and formulated recommendations for public authorities on improving state policy in the field of climate adaptation [5].

In assessing the impact of climate change on agroecosystem productivity and the risks of declining grain yields, O. Tarariko, T. Ilienko and T. Kuchma combined several sources of information: remote sensing data, the results of long-term field experiments and official statistics. Satellite observations made it possible to trace the spatio-temporal dynamics of crop condition and vegetation indices; the experimental data revealed crop responses to changing agroclimatic conditions under different cultivation technologies; and yield statistics provided the basis for a quantitative risk assessment and for forecasting gross grain harvests in the short and long term. Such an integrated approach makes it possible to link regional climate trends with field-level crop responses, which is essential for substantiating adaptation measures. The authors outlined the risks of degradation processes and proposed a mechanism for introducing soil- and water-conserving organization of land-use territory, together with remote sensing-based monitoring of the impact of climate change on agroecosystem productivity [12].

D. Hlushko assessed the nature and extent of the impact of climatic conditions on the yields of major agricultural crops in the Polissia zone and, on this basis, outlined prospects for the development of the region's agricultural sector under climate change. Ukrainian Polissia was chosen as the study area for several reasons. First, among the physical-geographical regions of Ukraine, Polissia exhibits the highest rate of climate change, which significantly affects the transformation of agricultural production. Second, since the consequences of climate change for agriculture largely depend on the natural conditions and specialisation of a region, it is advisable to study territories with relatively homogeneous climatic conditions and production structures, such as Polissia. Third, clarifying the dynamics of climate change and its impact on the region's agriculture provides a basis for timely adaptation measures capable of preventing adverse consequences [4].

O. Braslavska, O. Hrytsyk and T. Rozhi conducted a comprehensive study of the impact of climate change on the spatial differentiation and physicochemical properties of soils in the Steppe zone of Ukraine. Due to increasing aridisation and degradation of the soil cover, this region is among the most vulnerable. Analysis of long-term climate data revealed substantial changes in thermal and hydrological regimes. The study identified a significant spread of water and wind erosion, an increase in the area of eroded and secondarily salinised land, and a decline in the productivity of agricultural landscapes, which threatens the region's food security. Predictive modelling of soil cover dynamics under further warming indicates a contraction of chernozem areas and their transformation into less fertile chestnut and solonetzic soils. This process is accompanied by deterioration of agrochemical parameters and loss of biodiversity. The researchers substantiated the following directions for adapting land use to climate change: the introduction of resource-saving agricultural technologies; optimisation of the water regime through efficient irrigation systems using alternative water sources; precision farming with variable-rate fertiliser application; and the establishment of field-protective forest belts and buffer zones that curb erosion and stabilise the microclimate [1].

V. Melnyk-Shamrai, T. Kravchuk-Obodzinska, O. Alpatova and T. Sikach examined the relationship between the aridity gradient and biological indicators of soil condition in the Polissia, Forest-Steppe and

Steppe zones of Ukraine. The authors emphasise that rising temperatures, more frequent droughts, erosion and land-use intensification substantially reduce the biological activity of soils and their capacity for self-restoration. Analysis of microbial biomass carbon, enzymatic activity, specific microbial respiration (qCO_2) and the abundance of soil invertebrates revealed a clear zonal pattern. As aridity increases, soil biological activity declines while qCO_2 rises, indicating growing stress on the microbial community. In Polissia, biotic activity remains consistently high owing to the moderate climate and higher moisture. In the Forest-Steppe, indicators fluctuate seasonally, with dehydrogenase activity decreasing in summer because of moisture deficit. The strongest suppression is observed in the Steppe, where high temperatures and low precipitation create stressful conditions for soil biota. The authors concluded that biological parameters respond to climate change earlier than physicochemical ones. They can therefore be used as indicators for the early diagnosis of soil degradation and as a basis for developing adaptive farming strategies [7].

In their monograph, M. Ruda, T. Boiko and A. Shybanova examined the nature of complex and systemic risks arising from the non-linear interaction of natural and socio-economic systems under climate change. Particular attention is paid to the risks of soil degradation, as soil is one of the key components of ecosystems on whose condition the preservation of biodiversity and the resilience of territories depend. The methodological basis of the work is an analysis of the Plan of Action of the Technical Expert Group on Comprehensive Risk Management. The authors reveal the mechanisms by which cascading hazards emerge, whereby climatic factors trigger chain degradation processes in the soil cover and agricultural landscapes. The influence of concomitant factors, including poverty, demographic change and armed conflict, which increase the overall vulnerability of territories and limit their adaptive capacity, is analysed. The need to adopt a systemic approach to the assessment and management of climate risks is substantiated. The authors also propose principles of nature-based land-use planning aimed at preserving biodiversity, restoring the ecosystem functions of soil and enhancing the resilience of territorial communities to climate threats [10].

Thus, climate change is significantly transforming the conditions under which soils form and function, affecting their water, heat, and nutrient

regimes; the intensity of the biochemical processes of humification and mineralization of organic matter; and the resistance of the soil cover to erosion and deflation. A particular threat is posed by the mutual reinforcement of climatic and anthropogenic factors of degradation, where increasing aridity, and an increase in extreme precipitation and temperature anomalies compound the effects of irrational agricultural land use, disruption of crop rotations, destruction of protective forest stands, and – in wartime – technogenic and military damage to the soil cover. The synergistic effect of these factors creates persistent negative trends in land degradation (intensified erosion processes, degumification, secondary salinization, compaction, and physical degradation of soils), overcoming which requires systematic, scientifically grounded efforts at all levels of land resource management – from the national to the local community level.

Under these conditions, traditional approaches to land resource management – developed without due consideration of the dynamics of climate change – are gradually losing their effectiveness, creating an urgent need to revise the methodological foundations of land use, improve systems for monitoring soil quality, and implement modern approaches to forecasting the risks of land degradation.

The relevance of this study stems from the need for a comprehensive scientific understanding of the relationship between climate change and soil degradation processes, the identification of patterns in their spatial and temporal manifestation across various natural and climatic zones, as well as the development of effective organizational, economic, environmental, and technological mechanisms for adapting land use to new climatic realities. This takes on particular significance in the context of the need to align the state's food and environmental security objectives with the long-term goals of sustainable development and the post-war recovery of Ukraine's rural areas.

1. Climate-Driven Soil Degradation in Ukraine: Scale and Trends

Against the backdrop of climate change and significant human-induced pressure, the problem of soil degradation in Ukraine is becoming increasingly alarming, calling into question the country's stability on a national scale. Over the past decades, the country has seen a steady trend toward the deterioration of the quantitative, structural, and qualitative

characteristics of the soil cover, leading to a progressive decline in its productive potential, posing immediate risks to food security, and resulting in serious environmental consequences. Thus, the protection and restoration of soil resources are a priority for ensuring the country's sustainable development and preserving its wealth and stability in the face of contemporary environmental challenges.

According to data published in 2024, Ukraine has a significant share of low-productivity soils (sandy, eroded, acidic, saline and solonetzic), degraded soils (up to 10–12 million hectares) and technogenically contaminated soils (up to 20% of arable land), which require measures to protect and restore their fertility. The total area of agricultural land affected by water erosion and slope aridity is 13.3 million hectares (32%), including 10.6 million hectares of arable land. Slope lands include 4.5 million hectares of moderately and severely eroded and xeromorphic soils, of which 68,000 hectares have completely lost their humus horizon. More than 6 million hectares are subject to wind erosion, and in years with dust storms this figure rises to 20 million hectares. The quality of soil resources is also affected by other adverse factors, such as salinization, solonetzization, waterlogging and excessive aridity, which is very close to desertification. In recent years, Ukrainian agriculture has been dominated by an unbalanced, nutrient-deficient farming system. Low application rates of manure (less than 1 t/ha) and mineral fertilizers (less than 100 kg/ha of active ingredient) do not ensure the restoration of soil fertility, and the NPK balance remains negative. As a result, soils have lost a significant part of their humus (up to 20–30%). In addition, more than 15 million hectares of land are affected by hostilities, where mechanical, erosion, physical, chemical, physicochemical and biological degradation processes are widespread, including compaction by heavy military vehicles, disruption of the soil profile and changes in soil biota [8].

Current research indicates that the intensity of these degradation processes is increasing significantly under the influence of climate change. This primarily concerns global warming, understood as a persistent upward trend in the mean annual temperature of the near-surface atmosphere and the World Ocean, caused by the accumulation of greenhouse gases in the atmosphere (in particular carbon dioxide and methane), as well as aerosols and dust, which disrupt the Earth's natural heat balance. In Ukraine, the

mean annual temperature has risen by more than 2 °C since the beginning of the 20th century, including by 1.2 °C over the last three decades [5].

Figure 1 shows the average annual temperature in Ukraine for each decade from 1901 to 2019. The data illustrates a steady increase in temperature, highlighting the impact of climate change on regional climatic conditions.

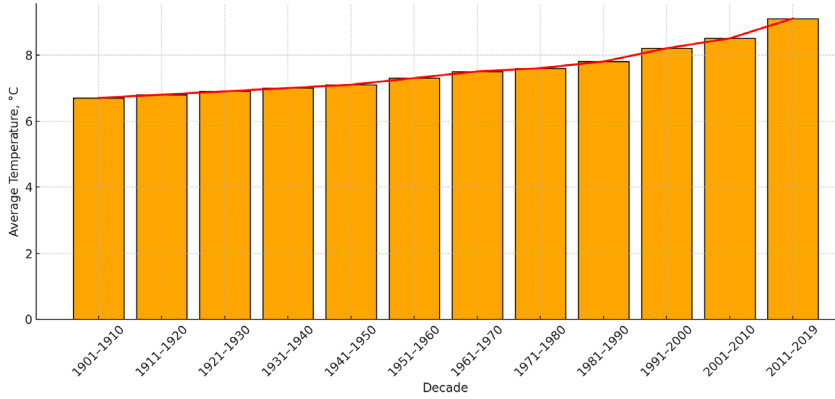


Figure 1. Average Annual Temperature in Ukraine [5]

The decadal averaging presented in Figure 1 captures the overall direction of the process well, but conceals its intensity over the final segment of the series: averaging smooths out record values and does not allow the current rate of change in the temperature regime to be assessed. It is therefore appropriate to examine the most recent six-year period separately, at annual resolution, comparing the observed values with the current 1991–2020 climatic norm (Fig. 2).

The data underlying Figure 2 were compiled from various agrometeorological reviews of the Ukrainian Hydrometeorological Center; the 1991–2020 climate normal is +9.1 °C (Table 1).

The dynamics of 2020–2025 confirm that the temperature increase recorded in the decadal averages has shifted to a pattern of persistent exceedance of the climate normal. Over the last six years, the mean annual temperature has never fallen below the normal. The mean value for the period is +10.4 °C, which is 1.3 °C above the 1991–2020 normal, a baseline that itself already reflects the warming of previous decades.

The 2024 maximum (+11.5 °C, a deviation of +2.4 °C) is the highest in the entire period of instrumental observations. The year 2021 is particularly revealing: formally it "matched the normal", yet against the rest of the series it appears to be an isolated exception rather than a return to the previous temperature regime.

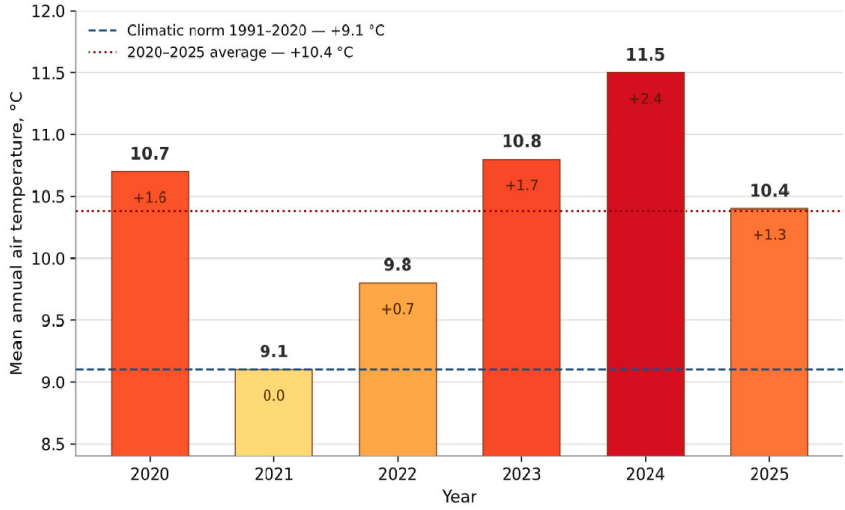


Figure 2. Mean annual air temperature in Ukraine, 2020–2025, against the 1991–2020 climatic norm. Compiled from operational data of the Ukrainian Hydrometeorological Centre [13]

Table 1

Mean annual air temperature in Ukraine in 2020–2025 and its deviation from the 1991–2020 climate normal

Year	Mean annual temperature, °C	Deviation from the normal, °C
2020	+10,7	+1,6
2021	+9,1	0,0
2022	+9,8	+0,7
2023	+10,8	+1,7
2024	+11,5	+2,4
2025	+10,4	+1,3
Mean, 2020–2025	+10,4	+1,3

The indicators shown in Figure 2 describe near-surface air temperature, an integral indicator that is convenient for comparing years but insufficient for assessing the condition of land resources. For soils, the decisive factor is the temperature regime of the root zone, where the mineralization of organic matter, moisture exchange and yield formation take place. Moreover, the soil's response to warming is not a simple reflection of the atmospheric one: the warming signal is amplified in the soil.

Extreme temperatures in the soil develop considerably faster than in the air, and the number of days with excessive heat in the soil is increasing twice as fast as in the atmosphere. Soil moisture plays a key role; it depends on vegetation cover and land-use practices, which indicates a direct influence of human activity on climate dynamics. By providing shade, vegetation cover substantially lowers soil temperature and dampens the amplitude of diurnal and seasonal fluctuations. The introduction of crop rotations, improved tillage practices and the retention of crop residues directly affect the soil temperature regime and can either amplify or mitigate the effects of global warming at the local level. Thus, soil temperature is an important indicator of the state of the climate system, closely linked to land use, biodiversity and the carbon cycle [6].

At the same time, soil temperature, as an important component of the climate system, has long received insufficient attention from researchers due to the difficulty of monitoring it. This is because, unlike air temperature, which is systematically measured by meteorological networks, soil temperature requires specialized equipment for measurements at different depths, which has complicated the development of reliable databases.

Further climate change and its impact on agriculture may follow one of two scenarios: arid (dry) or humid (wet). Under the humid scenario, yields of almost all agricultural crops are expected to increase by 20–25% in the medium term. Under the arid scenario, grain yields will decline rapidly throughout the Forest-Steppe zone of Ukraine. Under arid warming, by the mid-21st century increasing aridity may become the main negative manifestation of climate change in the country's most fertile regions: the decline in grain yields may exceed 20–25%, with critical consequences for the economy of the Central Forest-Steppe. In the Central Left-Bank Forest-Steppe, the most intense downward trend in total moisture input has been observed since 1998–2004: from 600 to 500 mm (2010–2014), with a slight

increase to 530 mm in 2020–2022. This results in a pronounced negative moisture balance during the warm season, reaching 120–150 mm [2].

In the central Forest-Steppe of Ukraine, where agricultural outcomes depend largely on weather conditions, adaptation to climate change should be regarded as a purposeful adjustment of natural and economic systems to actual and expected climatic impacts. Its aim is not only to reduce the adverse effects of warming but also to take advantage of the opportunities it creates. Adaptation measures should therefore be developed in advance and on a sound scientific basis. They should ensure the rational use of additional heat resources while reducing the risks of extreme weather events. Among these, droughts pose the greatest threat, as their intensity and spatial extent are increasing: they degrade the ecological condition of agricultural landscapes and reduce the productivity of agroecosystems [2].

To prevent further depletion of the soil cover and loss of its productivity, and to enhance its capacity to adapt to climate change, it is advisable to implement a set of measures:

– reducing greenhouse gas emissions from tillage by introducing resource-saving technologies that minimize soil disturbance and fuel consumption, together with systems for monitoring soil CO_2 and N_2O emissions. Reliable emission data would provide a basis for subsequent compensation mechanisms and allow land users to benefit from carbon markets;

– restoring soil organic carbon and improving soil fertility through the systematic application of organic fertilizers, restoration of the humus layer on eroded and xeromorphic soils, and agroforestry practices that protect against erosion, improve soil water-physical properties and ensure long-term accumulation of organic matter;

– applying soil conservation technologies, including contour tillage on sloping land, strip cropping and crop rotations dominated by crops that improve soil structure and biological activity, such as perennial grasses and legumes. Such rotations reduce surface runoff, increase infiltration and help maintain a positive humus balance;

– introducing adaptive land-use management based on the assessment of soil moisture availability and temperature regime by land-use type. Regular assessment of these parameters makes it possible to adjust crop structure, sowing dates and cultivation technologies to changing agroclimatic

conditions and to identify areas where the current type of use is no longer sustainable;

– using GIS technologies to identify areas at risk of soil degradation through spatial analysis of remote sensing data, digital elevation models and long-term agrochemical surveys, in order to implement soil conservation measures at the national and regional levels;

– developing adaptive land-use models at the level of territorial communities that take into account local climate change, soil and ecological conditions, and the socio-economic characteristics of specific territories. Integrated into comprehensive spatial development plans and land management documentation, such models translate national adaptation priorities into concrete spatial decisions for specific land plots;

– integrating soil conservation measures into low-carbon agricultural development policy through national and regional programmes that provide financial compensation to land users for preserving and restoring soil ecosystem functions, in particular carbon sequestration, maintenance of biological activity and regulation of the water regime;

– incorporating soil protection into agricultural climate strategies to ensure consistency between decarbonization measures and the preservation of soil fertility and carbon storage capacity. This helps avoid situations where emission reduction measures, such as the large-scale removal of crop residues for bioenergy, deplete soil organic matter and undermine the long-term productivity of land.

These measures should be viewed not as stand-alone actions but as components to be integrated into the overall system of soil protection and low-carbon development of modern agricultural production, and of farming in particular. Fragmented implementation of individual practices cannot ensure sustainable results and may often lead to only partial effectiveness or even counterproductive outcomes. Only coordinated interaction between agronomic, organizational and economic, legal and financial instruments can create synergy among them and turn them into an effective mechanism for preserving the country's soil potential, on which food security and ecological balance depend in the long term.

Land degradation is increasingly emerging as one of the key consequences of climate change and is becoming one of the most pressing problems, whose scale and complexity extend far beyond the purely

agronomic domain. It therefore requires in-depth scientific understanding and a coordinated management response in the face of mounting climate challenges.

2. Aim and Objectives of the Study

The aim of the study is to examine the impact of climate change on soil degradation processes and to substantiate scientific approaches and practical directions for adapting land-use systems aimed at minimizing adverse environmental and agricultural production consequences, maintaining stable soil fertility and enhancing the resilience of the agricultural sector to climate challenges.

To achieve this aim, the following objectives were set:

– to analyse current trends in mean annual air temperature in Ukraine and its deviations from the 1991–2020 climate normal in order to determine whether the warming observed in decadal averages has become persistent;

– to identify the mechanisms through which climate warming, changes in moisture supply and rising soil temperature intensify soil degradation;

– to summarize the findings of Ukrainian researchers on degradation factors and approaches to land-use adaptation, including the use of GIS and remote sensing for identifying degraded and uncultivated land;

– to identify the main directions of land-use adaptation to climate change and to define their content, implementation instruments and expected results, systematizing them in a form suitable for practical use in land management;

– to justify the interconnections between these directions as a basis for an integrated management model, taking into account the challenges of post-conflict recovery in de-occupied and frontline territories.

3. Principles of Land-Use Adaptation

Under climate change, modern land-use systems require environmentally balanced agricultural practices that simultaneously ensure the production of environmentally safe products, economic returns from farming activities and the preservation of soil fertility. This is particularly relevant for Ukraine in the context of hostilities and increased anthropogenic pressure on natural resources.

Aligning national policy with European environmental protection practices is a prerequisite for effective adaptation. This concerns the

implementation of the EU Soil Strategy, the UN Sustainable Development Goals and other international policy documents.

Accordingly, it is necessary to accelerate the integration of climate change adaptation directions into national policy, in parallel with climate change mitigation policies.

These directions include regulatory and institutional, monitoring, organizational and land management, technological, agrochemical, environmental, agro-energy, economic, and information and awareness-raising directions.

Below, the content of each direction is described in terms of improving soil condition for the adaptation of Ukraine's agricultural production to climate change, together with its practical implementation and its economic effect in improving soil quality.

4. Regulatory and Institutional Framework for Soil Protection

Given the growing challenges posed by climate change, a legislative and regulatory framework for soil protection and sustainable land use becomes crucial. Such a framework should not only address current environmental challenges but also provide adaptive response mechanisms. In this regard, the legal and regulatory environment should cover the development of standards for permissible soil loads that take into account climate zones and land-use types; the introduction of mandatory soil condition certification as a tool for systematic monitoring and early detection of degradation processes; stricter control over compliance with scientifically sound crop rotations and the implementation of anti-erosion measures, especially in areas of high climate risk; and the integration of environmental requirements into land policy, including ecosystem-based approaches to resource management. These measures will provide a legal and managerial basis for a model of environmentally safe and climate-adapted farming that encourages a responsible attitude towards land as a finite and strategic resource.

This direction also involves aligning national land policy with strategic documents on climate change adaptation and with the relevant instruments of the European Union, in particular the conditionality requirements of the EU Common Agricultural Policy and the standards for Good Agricultural and Environmental Condition of land (GAEC), which is of practical importance in light of Ukraine's European integration commitments.

5. Monitoring of Land Resources

The monitoring direction is of strategic importance for adaptive and science-based land resource management under climate change. It involves expanding the functional capabilities of systems for observing soil quality, the biophysical characteristics of land and the ecosystem services it provides. In practice, this is achieved through geographic information systems (GIS), satellite remote sensing, drone-based monitoring and vegetation index analysis (e.g. NDVI) to identify degraded, erosion-prone and water-stressed areas. The use of NDVI time series has proven effective for detecting agricultural land that has been withdrawn from cultivation, including as a result of hostilities [12]. Integrating monitoring results with State Land Cadastre data makes it possible to link identified risks to specific land plots and land users. Open digital databases provide transparent access to environmental information for all stakeholders. In economic terms, such a system makes it possible to identify risk areas in a timely manner, make adaptive management decisions, improve the efficiency of agricultural production processes and reduce losses caused by climate- and degradation-related threats. It also provides the evidence base needed to evaluate the effectiveness of the other adaptation directions.

6. Land Management Support for Land-Use Adaptation

Under global climate change, which aggravates soil degradation, biodiversity loss and declining productivity of agricultural landscapes, the organizational and land management direction becomes particularly important for rational land use. Combined with agrolandscape planning, zoning and land consolidation, it ensures the adaptation of land use to climate change by optimizing the structure of land holdings with regard to the natural potential of territories and ecological feasibility. This direction is implemented in practice by withdrawing low-productivity, eroded and degraded land from cultivation, followed by afforestation, grassing or the creation of buffer conservation areas.

The implementation of these measures will produce environmental, economic and climate benefits. The economic benefit lies in lower costs of cultivating unproductive areas and more efficient use of resources. The environmental benefit consists in improving the condition of agricultural

landscapes through the restoration of natural vegetation, reduced water and wind erosion and a more stable microclimate. The climate benefit results from the increased carbon sequestration capacity of landscapes, enhanced biodiversity and the formation of ecosystem buffers that mitigate the impacts of extreme weather events.

7. Soil-conserving and resource-saving agricultural technologies

The increasing frequency of droughts, heavy precipitation and temperature fluctuations reinforces the importance of the technological direction. It is based on the introduction of soil-conserving, resource-saving and low-carbon agricultural technologies aimed at reducing the adverse environmental impact of agriculture and enhancing the capacity of the agricultural sector to adapt to climate challenges.

The implementation of these measures involves minimum or no-till technologies to preserve the natural soil structure; the application of organic fertilizers and green manures to restore soil biological activity; agroforestry measures and contour farming to reduce water erosion; and precision farming systems to optimize resource use and reduce greenhouse gas emissions.

The introduction of such technologies produces both environmental and economic benefits. These include reduced anthropogenic pressure on the soil cover and agrocenoses; preservation of soil structural integrity and increased biological activity and water-holding capacity of the soil; reduced erosion, especially under climate extremes such as heavy rainfall and drought; and lower costs of tillage, fuels and lubricants, and plant protection products. This approach increases the adaptability of agricultural production to climate change and strengthens the resilience of agroecosystems in the long term.

8. Restoration of Soil Organic Matter

The agrochemical direction is key to adaptive and sustainable farming under climate change, which causes dehumification, depletion of soil nutrients and declining soil productivity. Changes in temperature regime, fluctuations in moisture, frequent droughts and erosion make it difficult to maintain soil fertility. The priority is therefore the use of both traditional (manure, compost) and non-traditional sources of organic matter, such

as crop residues, chopped straw, green manures, and maize and rapeseed residues. They not only provide plant nutrition but also stabilize the soil-ecological balance.

This approach makes it possible to slow down dehumification, maintain a non-deficit humus balance, activate soil biota, improve water retention and reduce erosion. At the same time, the need for mineral fertilizers and resource inputs decreases, while the ecological condition of land and crop quality in terms of protein, sugar, vitamin and mineral content improve. This strengthens agroecosystems, helps maintain ecological balance and contributes to food security under global change.

9. Greening of Agricultural Production

Under climate change, the environmental direction involves developing environmentally balanced and resource-efficient farming based on the principles of climate-smart agriculture. This concept pursues three interrelated goals: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing greenhouse gas emissions where possible [3].

This approach aims to reduce chemical pressure on the environment and greenhouse gas emissions, to abandon the excessive use of synthetic fertilizers and pesticides, to shift to organic production and to introduce soil-conserving non-inversion tillage technologies. Particular attention should be paid to nitrogen fertilizers, since their excessive or poorly timed application is a major source of nitrous oxide emissions from agricultural soils. In response to climate challenges, this model promotes biodiversity conservation, the adaptation of agroecosystems to extreme weather, improved soil condition and more efficient water conservation. At the same time, the transition to organic production may be accompanied by lower yields in the initial years, so it should be implemented gradually and supported by appropriate advisory and financial mechanisms. Its implementation requires adequate legal, institutional and economic support to establish a system of environmentally safe and long-term land use in line with the principles of sustainable development.

10. Agro-energy Use of Degraded Land

Under climate change, the agro-energy direction serves as a multifunctional instrument that combines several strategic public policy

objectives: achieving energy independence, adapting to climate challenges and ensuring sustainable land use. It consists in growing energy crops (miscanthus, energy willow, poplar, paulownia, etc.) on low-productivity, eroded, disturbed or contaminated land that is unsuitable for food production but is not withdrawn from economic use. This approach ensures the rational use of the resource potential of disturbed land without competing with the food sector. In a broader environmental and climate context, it helps reduce greenhouse gas emissions by replacing fossil fuels with renewable energy sources, strengthens the energy autonomy of regions, and improves the state of the environment and biospheric balance. Energy crops can also perform anti-erosion, reclamation and remediation functions, restoring the ecological potential of degraded land. From an economic perspective, bioenergy diversifies agricultural production, creates additional sources of income for farmers and communities, and develops local value chains such as biomass processing and the production of biofuels and biogas. In the long term, it may become an important component of the green transformation of the agricultural sector and be integrated into national and international climate strategies.

Thus, the agro-energy direction should be regarded as a comprehensive instrument of spatial land-use planning capable of simultaneously addressing, on a single methodological basis, three strategic priorities of sustainable rural development: food security (by keeping productive land available for food production), energy independence (through the development of local bioenergy infrastructure) and the ecological resilience of agricultural landscapes under climate change.

11. Agri-Environmental Insurance Against Climate Risks

Under climate change, the economic direction is gaining strategic importance, in particular through the development of agri-environmental insurance as one of the key mechanisms for enhancing the financial and climate resilience of the agricultural sector. This involves introducing instruments that make it possible to insure soil fertility and agricultural production against risks associated with land degradation, erosion, moisture deficit, resource depletion and the increasing frequency of climate extremes such as droughts, heavy rainfall and frosts.

Under current conditions, this approach reduces the risk of income losses caused by lower yields, while encouraging the adoption of soil-conserving technologies, organic farming and agrolandscape optimization. Agri-environmental insurance may include index-based approaches using parameters such as soil moisture, temperature regime and NDVI. In a broader context, it lays the groundwork for reorienting agricultural policy towards a green economy, encourages long-term investment in natural capital conservation, promotes the development of a market for ecosystem services and supports the achievement of the Sustainable Development Goals amid global climate instability.

Thus, the relevance of this direction is determined by a number of interrelated factors: growing climate risks, the need for financial protection of landowners and land users, the creation of economic incentives for sustainable land use, and the development of an appropriate institutional framework.

12. Information and Awareness-Raising Support for Adaptation

Under climate change, the information and awareness-raising direction is of key importance for shaping a new paradigm of sustainable and responsible land use. It involves systematically raising environmental and climate awareness among agricultural producers, local communities and society as a whole regarding the consequences of soil degradation, climate risks and modern technologies for preventing them. In practice, this direction is implemented at three interrelated levels: educational, digital and information, and institutional and partnership.

The educational level is implemented through training sessions, seminars and field demonstrations for landowners holding land shares, tenants, family farms and large agricultural holdings on soil-conserving tillage, organic production and climate-adaptive practices, as well as through the inclusion of these topics in professional development programmes for land management and agronomy specialists. In this context, it is particularly important to prepare educational and practice-oriented materials and to establish demonstration sites adapted both to regional soil and climate conditions and to the specific features of post-conflict territorial recovery. This means taking into account both the zonal differentiation in warming rates and soil cover vulnerability and the specific tasks arising in de-occupied

and frontline territories: diagnosing disturbed land, sequencing restoration measures and returning plots to economic use after demining is completed.

The digital and information level involves the development of online platforms for soil condition monitoring and for sharing knowledge and best agri-environmental solutions with a wide range of users. Such platforms can integrate Earth remote sensing data, geoinformation services and interactive databases, providing producers with rapid access to up-to-date information on the condition of land resources and recommended farming practices.

The institutional and partnership level is based on cooperation between research institutions, higher education institutions, public authorities, civil society organizations and international partners. Such cooperation significantly increases the effectiveness of information and awareness-raising activities, as it makes it possible to accumulate and disseminate best practices, including European experience in adapting agriculture to climate change.

The outcomes of this direction include improved professional skills of producers, faster adoption of innovative technologies and higher efficiency of agricultural production. Equally important is its long-term effect on land-use culture: as land users become more aware of climate risks and the consequences of soil degradation, their decisions increasingly shift from maximizing short-term yields to preserving the productive potential of land. This, in turn, builds public demand for sustainable environmental practices and strengthens support for other adaptation directions, from regulatory requirements to economic incentives. Taken together, these effects ultimately contribute to the adaptation of the agricultural sector to climate change.

13. Systematization of Adaptation Directions

The directions of adaptive land use, the instruments for their implementation and the expected results are summarized in Table 2. The table brings together the provisions discussed above and shows that each direction has its own set of instruments and expected results, while together they form a coherent system of complementary measures for adapting land use to climate change.

Table 2

Key directions of land-use adaptation to climate change: implementation instruments and expected results

Direction	Implementation instruments	Expected results
Regulatory and institutional	Adapting legislation, developing standards, integration into development strategies	Legal and managerial basis for environmentally safe and climate-adapted land use
Monitoring	GIS, Earth remote sensing data, NDVI, digital databases	Rapid identification of environmentally vulnerable areas, informed management decisions
Organizational and land management	Agrolandscape planning, land consolidation, agri-environmental zoning	Limiting adverse impacts on soils, optimizing land-use structure
Technological	Non-inversion tillage, science-based crop rotations, mulching with organic materials	Preservation of soil structure, slower erosion, higher soil water-holding capacity
Agrochemical	Traditional (manure, compost) and non-traditional (crop residues, green manures, etc.) sources of organic matter	Restoration of the humus horizon, higher soil fertility
Environmental	Transition to organic production, minimal use of pesticides and mineral fertilizers	Improved environmental condition, biodiversity conservation
Agro-energy	Growing energy crops on low-productivity and degraded land, closed bioenergy cycles	Additional source of income while reducing pressure on productive land
Economic	Agri-environmental insurance, support for investment projects	Lower financial risks, more stable incomes of agricultural producers
Information and awareness-raising	Training sessions, seminars, demonstration sites, digital online platforms	Active adoption of innovative technologies, public demand for sustainable environmental practices

CONCLUSIONS

The analysis confirmed that climate warming in Ukraine has moved into a phase of persistent exceedance of the climate normal: in 2020–2025 the mean annual air temperature never fell below the 1991–2020 normal, and the increasing moisture deficit and faster intensification of soil heat

extremes further accelerate degradation processes. Under these conditions, slowing down degradation, preventing further depletion of the soil cover and preserving its productive potential require a shift from isolated soil conservation measures to the integrated implementation of interdisciplinary adaptation directions. This shift is dictated by the very nature of the problem: soil degradation results from the combined effect of climatic, technological, economic and institutional factors, so acting on any one of them in isolation produces limited and unstable results, and gains achieved in one area may be offset by losses in another. These directions are regulatory and institutional, monitoring, organizational and land management, technological, agrochemical, environmental, agro-energy, economic, and information and awareness-raising. Each has its own object of influence and its own implementation instruments, yet their effectiveness is determined not by the sum of individual effects but by the nature of the interconnections between them. Only together do they form a systemic model of climate-adapted and environmentally oriented soil resource management, in which:

– the regulatory and institutional direction creates the legal, strategic and regulatory conditions without which other adaptation mechanisms remain fragmented and dependent on the initiative of individual land users;

– the monitoring direction provides an objective assessment of soil condition, spatial diagnosis of degradation risks and measurement of the effectiveness of the measures taken, enabling timely adjustment of management decisions at the level of territorial communities and land users;

– the organizational and land management direction, combined with agrolandscape planning, zoning and land consolidation, adapts land use to climate change by optimizing the structure of land holdings with regard to the natural potential of territories and ecological feasibility;

– the technological direction focuses on soil-conserving and resource-saving tillage technologies aimed at minimizing mechanical disturbance of the soil profile and conserving moisture;

– the agrochemical direction ensures balanced plant nutrition, restoration of soil nutrient status and humus balance, and improvement of soil agrochemical properties, with the ultimate goal of achieving a non-deficit balance of humus and major nutrients within crop rotations;

– the environmental direction ensures the long-term ecosystem resilience and value of agricultural landscapes and covers optimizing the

ratio of land types to an ecologically sound level, conserving degraded and low-productivity land, establishing field-protective forest belts, preserving soil biodiversity and restoring regulating ecosystem services (carbon sequestration, water regulation and erosion control);

– the agro-energy direction is an additional innovative component that offers an alternative use of low-productivity and degraded land, reducing economic pressure on the main agricultural land. By growing energy crops on such land, it keeps the land in economic use without intensive cultivation, while contributing to erosion control, the substitution of fossil fuels and new sources of income for territorial communities;

– the economic direction involves creating financial instruments that provide lasting incentives for soil-conserving farming, in particular agri-environmental insurance and investment in environmentally sound and climate-adapted solutions;

– the information and awareness-raising direction fosters a conscious attitude to soil protection among land users, disseminates knowledge and supports the gradual transformation of land-use culture. Its effectiveness lies in changing not individual technological choices but the criteria by which land users make them, shifting the evaluation of farming activities from short-term yields to preserving the productive potential of land.

Thus, each of the identified directions performs its own function within the model, and their combination ensures the integrity of the management process. The regulatory and institutional direction makes requirements binding and sets the legal framework for land use, while the monitoring direction provides feedback, verifies the results achieved and enables timely adjustment of management decisions. The organizational and land management direction ensures that measures are spatially linked to specific land plots through land management documentation, whereas the technological, agrochemical and environmental directions directly affect the condition of the soil cover, its fertility and its resistance to degradation. The agro-energy direction offers an alternative economic use of degraded and low-productivity land, making it possible to withdraw such land from intensive cultivation without losing economic returns. The economic direction creates incentives for soil-conserving behaviour among land users, and the information and awareness-raising direction increases their receptiveness to change and their willingness to adopt adaptation practices.

Only when interconnected do these directions form a systemic model of climate-adapted and environmentally oriented land resource management, in which regulatory, spatial, technological and motivational mechanisms work in concert towards a common goal: preserving land productivity under climate change.

Timely adaptation to climate change is one of the defining environmental, scientific and production challenges for Ukraine's agricultural sector. Addressing it requires alignment across three levels: the scientific level, through a deeper understanding of the mechanisms linking climate warming to soil cover degradation; the managerial level, through the legal establishment of soil protection requirements and their spatial linkage in land management documentation; and the production level, through actual changes in farming technologies at the level of land users. In other words, scientific justification without institutional consolidation remains a recommendation, and a regulatory requirement without an economic incentive remains a formality. Future research in this area should move from a qualitative description of adaptation measures to their quantitative justification.

References:

1. Braslavska, O., Hrytsyk, O., & Rozhi, T. (2025). Vplyv klimatychnykh zmin na prostorovyi rozpodil ta vlastyvosti gruntiv u Stepovii zoni Ukrainy [Impact of climate change on spatial distribution and properties of soils in the Steppe zone of Ukraine]. *Prostorovyi rozvytok*, (11), 557–573. DOI: https://doi.org/10.32347/2786-7269.2025.11.557-573

2. Demydenko, O. (2023, December 22). Vikova zmina klimatu ta produktyvnosti ahrotsenoziv tsentralnoho Lisostepu Ukrainy [Secular changes in climate and agrocenosis productivity in the Central Forest-Steppe of Ukraine]. *Ahronomiia sohodni*. Available at: https://agronomy.com.ua/statti/2155-vikova-zmina-klimatu-ta-produktyvnosti-ahrotsenoziv-tsentralnoho-lisostepu-ukrainy.html

3. Food and Agriculture Organization of the United Nations. (2013). *Climate-smart agriculture sourcebook*. Available at: https://www.fao.org/climate-smart-agriculture-sourcebook/concept/module-a1-introducing-csa/a1-overview/en/

4. Hlushko, D. (2024). Vplyv klimatychnykh zmin na ahrarne vyrobnytstvo oblastei Ukrainskoho Polissia [Impact of climate change on agricultural production in Ukrainian Polissia]. *Naukovi zapysky Ternopilskoho natsionalnoho pedahohichnoho universytetu imeni Volodymyra Hnatiuka. Seriia: Heohrafiia*, *57*(2), 47–57. DOI: https://doi.org/10.25128/2519-4577.24.2.6

5. Ivaniuta, S. P., Kolomiiets, O. O., Malynovska, O. A., & Yakushenko, L. M. (2020). *Zmina klimatu: Naslidky ta zakhody adaptatsii* [Climate change: Consequences and adaptation measures] [Analytical report]. National Institute for Strategic Studies. Available at: https://niss.gov.ua/sites/default/files/2020-10/dop-climate-final-5_sait.pdf

6. Liudstvo nedootsiniuie problemu nahrivannia gruntu, zoseredzhuiuchys na pidvyshchenni temperatury povitria i vody – doslidzhennia [Humanity underestimates the problem of soil warming by focusing on rising air and water temperatures: A study]. (2023, October 3). *Teksty.org.ua*. Available at: https://texty.org.ua/fragments/110796/lyudstvo-nedoocinyuye-problemu-nahrivannya-gruntu-zoseredzhuyuchys-na-pidvyshenni-temperatury-povitrya-i-vody-doslidzhennya/

7. Melnyk-Shamrai, V. V., Kravchuk-Obodzinska, T. V., Alpatova, O. M., & Sikach, T. I. (2025). Biolohichni indykatory dehradatsii gruntiv u konteksti hlobalnykh klimatychnykh zmin [Biological indicators of soil degradation in the context of global climate change]. *Ahrarni innovatsii*, (33), 187–191. DOI: https://doi.org/10.32848/agrar.innov.2025.33.31

8. My yikh vtrachaiemo: Grunty Ukrainy bidniiut i dehraduiut [We are losing them: Ukraine's soils are becoming depleted and degraded]. (n.d.). SuperAgronom.com. Available at: https://superagronom.com/articles/727-mi-yih-vtrachayemo-grunti-ukrayini-bidniyut-i-degraduyut

9. Nebezpechni vyklyky dlia silskoho hospodarstva svitu i Ukrainy [Dangerous challenges for agriculture in the world and Ukraine]. (2025, April 11). ArtFieldS. Available at: https://artfields.com.ua/%D0%B2%D0%B8%D0%BA%D0%BB%D0%B8%D0%BA%D0%B8-%D0%B4%D0%BB%D1%8F-%D1%81%D0%B3-%D1%81%D0%B2%D1%96%D1%82%D1%83-%D1%96-%D1%83%D0%BA%D1%80%D0%B0%D1%97%D0%BD%D0%B8/

10. Ruda, M., Boiko, T., & Shybanova, A. (Comps.). (2025). *Kompleksna otsinka ryzykiv dehradatsii gruntiv unaslidok zmin klimatu: Pryrodooriientovane planuvannia dlia zberezhennia bioriznomanittia i vidnovlennia ekosystemy gruntu* [Comprehensive assessment of soil degradation risks due to climate change: Nature-based planning for biodiversity conservation and soil ecosystem restoration]. HO "MNH". DOI: https://doi.org/10.56287/8285-53-1

11. Shevchenko, O. V., Pron, O. S., & Chebotarova, I. V. (2024). Vplyv klimatychnykh zmin na dehradatsiiu zemel ta ahroekosystem [Impact of climate change on the degradation of land and agroecosystems]. *Balanced Nature Using*, (3), 81–88. DOI: https://doi.org/10.33730/2310-4678.3.2024.314921

12. Tarariko, O. H., Ilienko, T. V., & Kuchma, T. L. (2016). Vplyv zmin klimatu na produktyvnist ta valovi zbory zernovykh kultur: Analiz ta prohnoz [Impact of climate change on productivity and gross harvest of grain crops: Analysis and forecast]. *Ukrainian Geographical Journal*, (1), 14–22. DOI: https://doi.org/10.15407/ugz2016.01.014

13. Ukrainian Hydrometeorological Center. (n.d.). *Ahrometeorolohichni umovy: Ohliady za 2020–2025 rr.* [Agrometeorological conditions: Reviews for 2020–2025]. Available at: https://www.meteo.gov.ua