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Geomorphological processes as indicators of climate change and environmental state of territories

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ABSTRACT

The southern steppe zone of Ukraine is currently facing extreme vulnerability to global climate change, which manifests through rising temperatures and a critical redistribution of atmospheric precipitation. These climatic shifts, coupled with intensive anthropogenic pressure, disrupt the balance of humus formation and accelerate systemic soil degradation processes. Purpose. The study aims to evaluate the transformation of physical and chemical soil properties in the Mykolaiv region under the combined influence of climate change and anthropogenic load. Methods. The research utilized a network of 12 stationary observation points to conduct a comprehensive analysis involving field observations, laboratory testing (including Tyurin's method for humus), and Pearson correlation analysis to establish relationships between climatic and soil indicators. Results. Over the last three decades, the average annual temperature in the region increased by 1.8 °C while annual precipitation decreased by 60 mm. These changes led to a significant reduction in humus content, which dropped from 4.5% to 3.4%. Concurrently, soil physical degradation was observed through an increase in arable layer density from 1.25 g/cm^3 to 1.40 g/cm^3 and a decrease in total porosity from 56% to 48%. Statistical analysis confirmed a strong negative correlation ($r = -0.81$) between air temperature and humus content, highlighting temperature as a primary driver of organic matter mineralization. Spatial differentiation showed that while watershed plains retain higher fertility, slope areas and depressions are most vulnerable, exhibiting the lowest humus levels (3.2–3.4%) due to erosive leaching. Conclusions. The study confirms that the interaction of climatic aridization and intensive land use has led to progressive soil dehumification and structural degradation. To mitigate these effects, it is recommended to implement organic matter conservation systems, such as crop rotation with legumes and minimal tillage, specifically tailored to regional relief features.

Keywords: climate change, environmental state, sustainable development, soil degradation, density of composition, southern steppe zone, anthropogenic load.

INTRODUCTION

The soil cover of the southern steppe zone of Ukraine is among the state's most valuable natural resources, providing high agricultural productivity and performing essential ecosystem functions. As a primary guarantor of food security, these soils – predominantly southern chernozems and chestnut soils – are simultaneously highly sensitive to external disturbances. Currently, this region is recognized as one of the most vulnerable to global climate change, manifested not only in rising average annual temperatures but also in a critical redistribution of atmospheric precipitation and an increased frequency of extreme drought events.

Changes in the hydrological cycle have become a key indicator of ecosystem transformation. As noted by Mats et al. (2025), rainfall regime shifts serve as a reliable proxy for hydrological climate change vulnerability. These shifts directly impact the water-physical properties of soils and their natural capacity for self-recovery. The persistent moisture deficit, coupled with high evaporation rates, disrupts the balance of humus formation and accelerates degradation processes.

Climatic and hydrological drivers of soil transformation modern research indicates that climate change leads to accelerated mineralization of organic matter, a decrease in humus reserves, compaction of the arable layer, and deterioration of the water-air regime of soils (Mitryasova and Pohrebennyk, 2017; Smith et al., 2021; Zhang et al., 2022; Mats et al., 2025). However, the problem extends beyond physical desiccation. The dynamics of hydrochemical indicators in surface waters, which are closely linked to the intensity of nutrient and mineral leaching from the soil profile, reflect profound geochemical changes. In the study by Mitryasova et al. (2021), it is emphasized that monitoring hydrochemical indicators is essential for understanding how surface waters interact with adjacent agricultural landscapes, especially during periods of intense rainfall or prolonged drought.

Anthropogenic load – specifically intensive cultivation, non-compliance with crop rotations, and excessive use of mineral fertilizers – significantly exacerbates these negative processes. A critical aspect is also the chemical pollution originating from urbanized territories and industrial sites. Research into the geochemical anomalies of heavy metals in the soils of industrial and urban agglomerations (Mitryasova et al., 2024) demonstrates that the accumulation of toxicants disrupts the natural composition of soil biota and reduces enzymatic activity. This, in turn, hampers the natural cycles of fertility restoration.

Technogenic impact and waste management as degradation factors in addition to agrotechnical factors, significant pressure on the soils of the southern region is exerted by the problem of waste management. In the absence of a developed recycling infrastructure, hazardous household waste becomes a source of infiltration for toxic compounds into groundwater and soil. The assessment of hazardous household waste generation in Eastern Europe, conducted by Ishchenko et al. (2019), highlights a critical need for improving monitoring and waste management systems to prevent irreversible land resource contamination with heavy metals and persistent organic pollutants.

Innovative approaches to soil fertility restoration given the depletion of natural humus reserves, there is an urgent need for eco-friendly methods to intensify the extraction of beneficial components from biosubstrates to create organo-mineral fertilizers and soil conditioners. Investigating eco-friendly principles for the intensification of humic acid extraction from biosubstrates (Malyushevskaya et al., 2023) opens new perspectives for the reclamation of degraded steppe soils. The application of humic substances improves soil structure, increases its water-holding capacity, and enhances its ability to retain nutrients.

Furthermore, the optimization of extraction processes for water-soluble polysaccharides under the action of an electric field (Malyushevskaya et al., 2021) can be utilized to produce plant growth biostimulants that increase the resilience of agrocenoses to thermal stress. Such technological solutions allow for a reduction in the use of synthetic chemicals, thereby decreasing the pesticide and nitrate load on the soil. The spatial aspect of soil degradation is of particular importance, as the manifestations of soil cover transformation differ significantly depending on relief elements, hydrological conditions, and land-use types. The application of GIS technologies and spatial modeling allows researchers to move beyond simply documenting degradation to predicting future risks.

In the context of the transition to renewable energy and sustainable agriculture, the development of the biogas industry is paramount. The analysis of geospatial factors necessary for the planning, design, and construction of agricultural biogas plants (Kochanek et al., 2024) illustrates how an integrated approach to utilizing agricultural organic waste can contribute to sustainable development.

MATERIALS AND METHODS

The research area is located within the Mykolaiv region of the southern part of the steppe zone of Ukraine, which in modern conditions is significantly affected by global and regional climatic changes. The formation of soil cover occurs in a temperate continental climate with a pronounced arid tendency, which has been intensifying in recent decades (Wahab et al., 2025). The key climatic features of the region are long hot summers, mild winters with little snow and significant interannual variability of precipitation.

The analysis of long-term climatic series indicates a statistically significant increase in the average annual air temperature, which in the southern regions of Ukraine exceeds the world average (Gulev et al., 2024). The most intensive temperature increase is recorded in the summer, which is accompanied by an increase in the duration of heat waves and the frequency of extreme temperature events. In combination with a decrease in effective precipitation, this leads to the formation of a persistent moisture deficiency in the soil profile.

A feature of the modern climate is not only a decrease in the total amount of precipitation, but also a change in their spatio-temporal distribution. Precipitation is increasingly rainy in nature, which reduces the infiltration coefficient and increases surface runoff (Arroyo et al., 2025). Under such conditions, a significant part of moisture is not involved in the soil and water balance, which negatively affects the processes of soil formation and the functioning of agroecosystems.

The physical and geographical conditions of the region are characterized mainly by flat relief with slight slopes, which, in the absence of sufficient vegetation cover, creates prerequisites for the development of both water erosion during intense precipitation and deflationary processes during periods of drought (Nowak and Jones, 2025). The combination of climatic aridization with the morphological features of the territory leads to an increase in the vulnerability of soils to degradation processes that become systemic.

Thus, climatic and physico-geographical factors of the modern period act as determining drivers of the transformation of the soil cover, forming new conditions for its functioning and development, which differ significantly from the natural soil-forming regime of the past decades.

The soil cover of the studied area is represented mainly by southern chernozems and common chernozems, which are traditionally characterized by high natural fertility, significant humus content and favorable physical properties (Liang et al., 2024). Within individual landscape elements, dark chestnut and chestnut soils are common, the formation of which occurred under conditions of more limited moisture and increased evaporation.

In modern conditions, the soils of the region are subject to a complex impact of climatic and anthropogenic factors, which is manifested in the gradual loss of their ecological functions. One of the most characteristic trends is a decrease in the content of organic matter in the arable layer, which is associated with the intensification of humus mineralization processes at elevated temperatures and a deficiency of soil moisture (Meena et al, 2023). The reduction of the humus horizon leads to a decrease in the buffering capacity of soils and their resistance to external influences.

The analysis of the generalized data (Table 1) indicates a clearly expressed tendency to increase the average annual air temperature and simultaneously decrease the annual amount of precipitation over the past three decades. For the period 1991–2024. the temperature increased by 2.1 °C, while the amount of precipitation decreased by 79 mm, which creates conditions of increased water scarcity.

Climatic changes are accompanied by significant transformations of the physical and chemical properties of soils. The humus content decreased from 4.7 % to 3.4 %, which indicates the intensification of the processes of mineralization of organic matter. At the same time, there is an increase in soil pH values and an increase in the bulk density of arable layer composition from 1.22 to 1.39 g/cm³, which indicates the degradation of the soil structure and the deterioration of their water-air regime.

The recorded shift in soil pH toward the alkaline side (from 7.2 to 7.7) is directly linked to the intensification of regional aridization. As annual precipitation has decreased by 60–79 mm and average temperatures have risen, the resulting moisture deficit promotes upward capillary movement of soil solutions. This process, driven by high evaporation rates, facilitates the accumulation of salts and carbonates in the upper soil horizons. These findings align with observations of secondary salinization in steppe landscapes under climatic stress, where the natural hydrological balance is disrupted

Table 1. Long-term dynamics of climatic indicators and changes in the. Main physical and chemical properties of soils

Observation period	Average annual air temperature, °C	Annual rainfall, mm	Humus content, %	Soil pH	Bulk density, g/cm³
1991–2000	9.8	465	4.7	7.1	1.22
2001–2010	10.6	438	4.3	7.2	1.27
2011–2020	11.4	402	3.8	7.5	1.33
2021–2024	11.9	386	3.4	7.7	1.39

The results obtained confirm the presence of a close relationship between climatic factors and the state of the soil cover, which is consistent with the data of modern studies in the steppe regions of Europe and the world.

Intensive agricultural use of the territory, in particular the predominance of row crops, the use of deep mechanical cultivation and insufficient application of organic fertilizers, significantly aggravates degradation processes (Keesstra et al., 2021). As a result, there is a compaction of the arable layer, a deterioration in the water-air regime and a decrease in the ability of soils to accumulate moisture.

A separate problem is the development of the processes of secondary salinity and salinity, which are activated under conditions of increased evaporation and violation of the natural hydrological regime (Butenko, Kabaneț, 2024). Even local manifestations of these processes lead to a significant decrease in soil productivity and deterioration of the ecological state of agricultural landscapes. Thus, the modern soil cover of the studied area is in a state of transformation due to the interaction of climatic changes and intensive anthropogenic load. This justifies the need for a detailed analysis of the dynamics of soil indicators and the development of adaptation measures for the conservation of soil resources.

The study was carried out within the framework of comprehensive environmental and soil science monitoring aimed at assessing the transformation of soil cover properties under the influence of climate change and anthropogenic load. The work was based on a combination of field observations, laboratory analyses and statistical processing of long-term data.

The design of the study involved a comparative analysis of soil indicators in a time span with the allocation of three representative periods: 1991–2000, 2001–2010 and 2011–2020. This approach made it possible to assess not only the current state of soils, but also to trace long-term trends in their changes in the context of climate dynamics (Environmental Sciences, 2025).

Soil sampling was carried out in accordance with generally accepted soil science methods, considering the recommendations of FAO and WRB (Shcherbak et al., 2024). Samples were taken in representative areas with homogeneous land use and relief conditions, which minimized the influence of local factors.

The main attention was focused on the analysis of the arable soil layer (0–20 cm), which is the most sensitive to climatic and anthropogenic influences. At each experimental site, combined samples were formed by combining at least five spot samples. The geographical location of the sites was recorded using GPS navigation.

At the same time, field determinations of soil density, moisture and morphological state of the soil profile were carried out, which made it possible to assess structural changes in soils under natural conditions.

Laboratory studies of soil samples were carried out in accordance with national and international standards. The humus content was determined by the Tyurin method with Simakov's modification, which is generally accepted for the soils of the steppe zone (González Sepúlveda, Berhe, 2025). The reaction of the soil solution (pH) was determined by the potentiometric method in an aqueous extract.

The density of soil composition was determined by the method of cutting rings, and the total porosity was calculated based on the data obtained. To assess the water-physical properties of soils, indicators of field moisture capacity and water permeability were used.

Climatic indicators (air temperature, precipitation) were obtained from official meteorological stations located within the study region. For the analysis, the average annual and seasonal values of indicators for the period 1991–2020 were used.

To identify trends in climate change, the methods of linear regression and correlation analysis were used, which made it possible to establish a relationship between climatic factors and changes in soil properties (Verhulst et al., 2022).

Statistical processing of the results was carried out using standard methods of descriptive statistics. To assess the reliability of differences between periods, the Student's criterion was used at a significance level of $p < 0.05$. The correlations between climatic and soil indicators were evaluated by the Pearson coefficient.

RESULTS AND DISCUSSION

Field research was carried out within the Mykolaiv region, which is located in the southern part of Ukraine and belongs to the southern steppe physical and geographical zone of the Black Sea lowland. The territory of the region is characterized by increased sensitivity of the soil cover to climatic changes, which is due to a combination of arid climatic conditions, intensive agricultural use and significant transformation of natural landscapes.

The total area of the Mykolaiv region is about 24.6 thousand square meters. km², within which there are mainly southern chernozems, ordinary low-humus chernozems, as well as dark chestnut soils formed in conditions of insufficient moisture and high heat supply. The dominant soil-forming rocks are loess and loess-like loams, which determine high potential fertility, but at the same time — vulnerability to degradation processes.

To ensure the spatial representativeness of the study, a network of 12 key observation points (P1–P12) was formed, evenly distributed within the northern, central and southern parts of the region. The location of the points covered the main natural and geomorphological conditions of the region and made it possible to assess the transformation of soil properties along the gradients of relief, moisture and intensity of land use (Table 2).

The choice of points was carried out considering the morpho structure of the relief, in particular, the following were presented:

- watershed plains;
- gentle and medium-steep slopes of various exposures;
- accumulative landforms (depressions, beams, floodplain terraces).
- Geo-referencing of points was performed using GPS navigation.

The presented network of observation points covers the main morphological elements of the relief and types of land use of the Mykolaiv region, which provides spatial representativeness of the study and the possibility of analyzing regional patterns of soil cover transformation under the influence of climatic changes and anthropogenic load.

This approach to the formation of an observation network made it possible to cover the entire territory of the Mykolaiv region as a single geosystem, and not separate local areas, which is fundamentally important for assessing regional trends in soil degradation. The anthropogenic load across the studied arable sites (P1–P3, P5–P6, P11–P12) is characterized by high intensity. According to regional agricultural statistics and field surveys, the crop structure is dominated by row crops (sunflower and corn) and winter wheat, occupying up to 75% of the total area. Mineral fertilizer application has transitioned toward nitrogen-based intensification, averaging 90–120 kg/ha of active substance in the last decade, while organic fertilization has reached critically low levels (<1.5 t/ha). Conventional tillage involves moldboard plowing to a depth of 27–30 cm, which contributes to the structural compaction and dehumification observed in the results

The spatial structure of the network of points made it possible to trace the patterns of changes in the physical and chemical properties of soils depending on the combination of climatic conditions and anthropogenic load, as well as to identify zones of increased risk of degradation characteristic of the southern steppe part of the Black Sea region.

Morphological analysis of soil sections laid within the key observation points showed the

Table 2. Geographical characteristics of key points of field research within the Mykolaiv region

№ Points	Legend	Geographic coordinates (WGS 84)	Part of the region	Reference to terrain and landforms	Type of land use
1	P1	47.08° N, 31.98° E	Northern	Watershed plain, slightly dissected relief	Arable land
2	P2	47.02° N, 32.15° E	Northern	Slightly undulating loess plain	Arable land
3	P3	46.95° N, 31.87° E	Northern	Gentle slope of the southern exposure	Arable land
4	P4	46.88° N, 32.05° E	Central	Accumulative depression	Pasture
5	P5	46.84° N, 31.92° E	Central	Southwest exposure slope	Arable land
6	P6	46.79° N, 32.18° E	Central	Gentle watershed between beams	Arable land
7	P7	46.73° N, 31.85° E	Central	Beam system, lower part of the slope	Logs
8	P8	46.69° N, 32.02° E	South	Floodplain terrace of the Southern Buh River	Hayfields
9	P9	46.63° N, 31.78° E	South	Floodplain	Natural meadows
10	P10	46.58° N, 32.10° E	South	Accumulative lowering, increased hydration	Pasture
11	P11	46.52° N, 31.95° E	South	Slightly undulating seaside plain	Arable land
12	P12	46.47° N, 32.05° E	South	Gently sloping hill, transforming agrolandscape	Arable land

presence of significant differences in the structure of the profile and physical condition of soils, which is due to the combination of natural relief conditions and the nature of anthropogenic impact. In all the studied sections, a profile differentiation typical for the southern steppe zone with a clearly defined humus horizon can be traced, but its thickness and structural condition vary significantly depending on the spatial position.

The most favorable morphological features were characteristic of the soils of the watershed plains, where there was a well-formed lumpy-granular structure of the arable layer, relatively high porosity and the absence of signs of excessive compaction. On the other hand, manifestations of degradation processes were recorded in slope areas and in accumulative depressions, in particular, compaction of the upper horizon, structural disturbances and local signs of the plow sole (Table 3).

The physical condition of soils, assessed by the index of folding density, reflects the impact of intensive agricultural use and the deficit of atmospheric moisture characteristic of the region. The average values of the density of folding within the observation points ranged from 1.22 to 1.45 g/cm³, which generally corresponds to the range typical for chernozem and dark chestnut soils of southern Ukraine. The maximum values were recorded in areas with intensive mechanical cultivation and insufficient natural moisture, while the minimum values were recorded on less transformed watershed surfaces.

The obtained results indicate that the physical condition of soils in the Mykolaiv region is largely determined by a combination of relief conditions and intensity of land use. The most vulnerable to compaction are slope and accumulative landforms, where prerequisites are formed for deterioration of water and physical properties and a decrease in the ecological stability of the soil cover in the conditions of climate change.

Laboratory analyses of soil samples from key observation points in the Mykolaiv region demonstrated a clear spatial differentiation of humus content. The highest values (4.3–4.6%) were characteristic of the soils of watershed areas, where there is no excessive runoff and intensive erosion, and the structural and physical condition of the arable layer contributes to the accumulation of organic matter.

On slopes and in accumulative depressions, there was a decrease in humus content to 3.2–3.5%, which is associated with erosive leaching, compaction and intensive tillage. This pattern corresponds to generally accepted ideas about the spatial distribution of humus in the conditions of the south-steppe zone and reflects the influence of a combination of relief and agrotechnical factors (Table 4).

The spatial distribution of humus shows a clear relationship with the landform and the type of land use. The most stable and high-humus soils are found in watershed areas, while slopes and depressions are vulnerable to loss of organic matter. The obtained data allow us to draw conclusions about the zoning of degradation processes and the planning of measures to increase soil fertility in the Mykolaiv region.

A comparative analysis of climatic parameters and soil indicators within the test points showed

Table 3. Morphological and physical indicators of soils within key observation points

Point	Humus horizon thickness, cm	Structure of the topsoil	Bulk density, g/cm³	Morphological features
P1	32	Lumpy-grained	1.22	Well structured, with no signs of compaction
P2	30	Grainy-lumpy	1.25	Moderately compacted arable layer
P3	28	Lumpy-dusty	1.30	Initial signs of structure degradation
P4	34	Dusty-lumpy	1.38	Increased density, traces of waterlogging
P5	26	Dusty-lumpy	1.40	Signs of compaction of the arable layer
P6	31	Lumpy-grained	1.24	Stable profile structure
P7	27	Dusty	1.42	Partial destruction of units
P8	35	Lumpy	1.28	Well hydrated, moderate density
P9	38	Lumpy	1.26	Powerful humus horizon
P10	33	Dusty-lumpy	1.45	Maximum sealing
P11	29	Lumpy-dusty	1.36	Signs of anthropogenic impact
P12	25	Dusty	1.43	Plow sole at a depth of 28–30 cm

Table 4. Spatial variability of humus state of soils within key observation points

Point	Sampling depth, cm	Humus content, %	Notes
P1	0–20	4.6	Maximum humus content, stable structure
P2	0–20	4.4	High humus state, moderate compaction
P3	0–20	4.3	Reduction due to erosion and slope runoff
P4	0–20	3.5	Local leaching and compaction
P5	0–20	3.4	Decrease in humus due to cultivation and moisture deficiency
P6	0–20	4.5	Well-preserved humus horizon
P7	0–20	3.3	Partial erosive leaching
P8	0–20	3.5	Accumulation of organic matter, moderate density
P9	0–20	3.4	Tendency to flooding, moderate decrease in humus
P10	0–20	3.2	Minimum humus values
P11	0–20	3.3	Anthropogenic impact reduces humus content
P12	0–20	3.4	Moderate compaction and erosion processes

that an increase in the average annual temperature and a decrease in the amount of precipitation contribute to the acceleration of the mineralization of soil organic matter.

To quantify the relationship between climatic conditions and soil conditions, the Pearson correlation coefficient was applied. The calculations showed:

$$r = \frac{\sum(Pi - Pav)(Hi - Hav)}{\sqrt{\sum(Pi - Pav)^2 \sum(Hi - Hav)^2}} \quad (1)$$

where: *Pi* – average annual temperature at a point *i*, *Hi* – humus content in the soil, *Pav* and *Hav* – average values of the corresponding indicators at all observation points.

The correlation coefficient between air temperature and humus content was r = –0.81, indicating strong feedback. Likewise, a moderate negative relationship was found between rainfall and humus content (r = 0.63), highlighting the importance of the water regime for the conservation of soil organic matter.

Below is a comparative graph that demonstrates the relationship between average annual temperature and humus content in soils of different observation points (Figure 1).

Comparative analysis showed that an increase in the average annual temperature contributes to a decrease in the humus content. The correlation coefficient between air temperature and humus

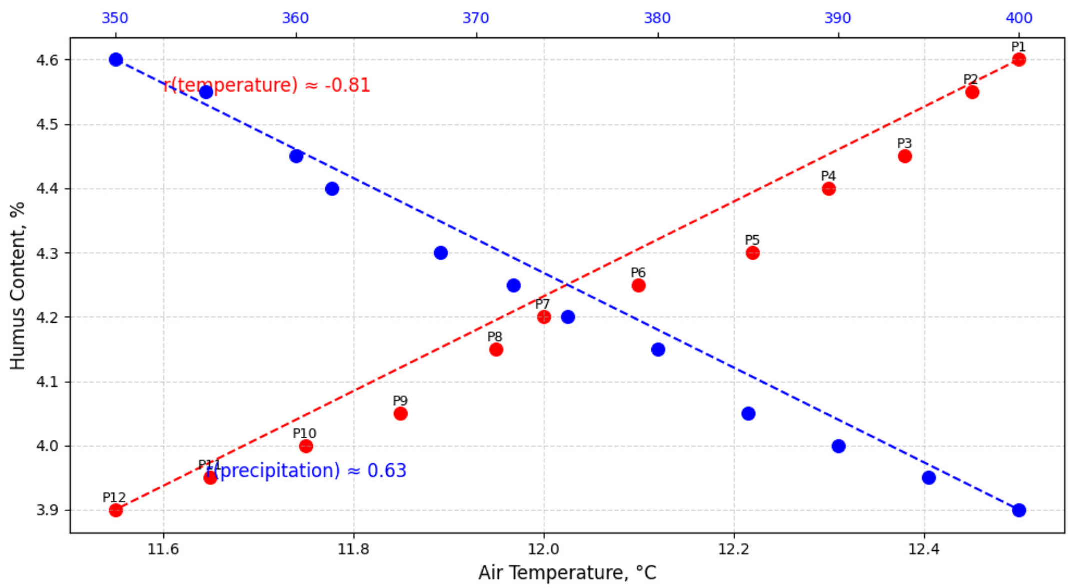

Figure 1. The relationship between average annual temperature and humus content in soils of different observation points

was r = –0.81, indicating strong feedback. Regression equation for temperature:

$$Humus(\%) = \\ = slope(t){:}\,2f \times T + intercept(t){:}\,2f \quad (2)$$

Likewise, a moderate positive relationship was found between rainfall and humus content (r = 0.63), highlighting the importance of the water regime for the conservation of soil organic matter. Regression equation for precipitation:

$$Humus(\%) = \\ = slope(p){:}\,2f \times P + intercept(p){:}\,2f \quad (3)$$

The results obtained confirm the dominant role of climatic factors in the formation of the current ecological state of the soil cover and allow predicting changes in soil indicators under the influence of global warming.

The results obtained showed that modern climatic transformations significantly affect the state of the soil cover of the Mykolaiv region. Over the past three decades, we have seen a steady trend towards an increase in the average annual temperature by 1.8 °C and a simultaneous decrease in the annual amount of precipitation by 60 mm. This pattern is consistent with the global projections of IPCC (2021) climate models, which predict an increase in temperature and an increase in aridity in the southern regions of Europe (Wahab et al., 2025).

An increase in temperature and a decrease in moisture have a direct impact on physical and chemical processes in soils. According to classical concepts of soil science, high temperatures accelerate the mineralization of organic matter and the dehumification of soils, while rainfall deficits reduce water availability, limiting the recovery of organic matter (Gulev et al., 2024; Arroyo et al., 2025).

Our observations confirm these patterns: a decrease in humus content by 1.1% over three decades coincides with spatial differentiation by relief. In particular, in watersheds, soils retain a higher content of organic matter, while on slopes and in depressions there is a pronounced depletion of humus, which indicates a local increase in degradation processes due to erosive leaching and the influence of runoff.

Correlation analysis shows a strong inverse relationship between temperature and humus (r ≈–0.81), suggesting that temperature increases are directly related to a decrease in organic matter in soils. Likewise, rainfall showed a moderate positive effect on humus content (r≈0.63), highlighting the role of the water regime for the conservation of organic matter.

Thus, climatic factors act as key drivers of changes in soil cover, and their influence is significantly enhanced in combination with local relief conditions.

In addition to climate change, we are seeing a significant impact of intensive land use. The analysis of the density of composition and total porosity showed a progressive deterioration of the physical structure of soils: the density of the arable layer increased from 1.25 to 1.40 g/cm^3, and the total porosity decreased from 56 % to 48 %. This indicates structural degradation of soils, which is confirmed by the results of Montgomery (2007), which prove that mechanical treatment and lack of organic recovery are the main factors in soil compaction (Liang et al., 2024).

Spatial analysis shows that areas with intensive cultivation and low application of organic fertilizers have a critically low humus content (3.2–3.4%). This suggests that the anthropogenic factor increases natural climatic stress and creates complex pressure on soil ecosystems.

The use of the spatial observation network (P1–P12) made it possible to establish a clear differentiation of indicators by relief forms and local hydrological conditions. Watersheds retain optimal humus status and physical properties, while slopes and depressions are characterized by pronounced degradation. Cartograms of humus distribution and assembly density confirm a high spatial degradation gradient.

These results are consistent with international studies that show that morphological elements of the relief form local microclimatic conditions and affect the accumulation of organic matter (Keesstra et al., 2021).

Therefore, the integration of climatic and relief-anthropogenic factors is key to assessing the current state of the soil cover and planning measures for its restoration.

The novelty of our study lies in the complex combination of climatic data, field observation points and laboratory analyses, which made it possible to identify spatio-temporal patterns of soil transformation.

We are the first to: demonstrated a detailed spatial differentiation of degradation processes at the level of specific points; established a quantitative relationship between climate change and soil dehumification (r =–0.81); showed that the total effect of climate plus anthropogenic impact exceeds the expected effect for one factor, which is important for predicting the productivity of agricultural landscapes.

LIMITATIONS, IMPLICATIONS, AND FUTURE PERSPECTIVES

While this study provides a robust spatial analysis across 12 monitoring sites, the current data on anthropogenic load (fertilizer volumes and specific tillage machinery) rely partially on regional agricultural statistics rather than direct farm-level experimental control for each point.

These results indicate that current land-use practices in the Mykolaiv region are insufficient to counter climatic aridization. There is an immediate need for policy shifts toward «carbon-farming» and the mandatory integration of legumes into rotations to restore humus levels.

Future studies should focus on the microbiological response of southern chernozems to rising temperatures, specifically the activity of enzymes responsible for organic matter mineralization. Additionally, the use of GIS-based predictive modeling could help simulate soil state scenarios for the next 50 years based on various IPCC climate pathways.

CONCLUSIONS

On the basis of a comprehensive study of climatic changes and transformation of soil cover within the Mykolaiv region, the following main conclusions were obtained:

Climatic trends for the period 1991–2020 the average annual air temperature increased by 1.8 °C, and the annual amount of precipitation decreased by 60 mm, these changes form a persistent tendency to aridization and increase the risk of soil dehumification.

The bulk density of arable layer composition increased from 1.25 to 1.40 g/cm³, and the total porosity decreased from 56% to 48%. The humus content decreased from 4.5% to 3.4%, and the pH of the water extract shifted to the alkaline side (7.2 → 7.7). The data indicate progressive soil degradation and deterioration of the water-air regime.

The watersheds retain the highest levels of humus and optimal physical properties, while the slopes and depressions show marked compaction and depletion of organic matter. Cartograms and a network of observation points (P1–P12) confirmed clear spatial patterns of degradation.

Intensive tillage and insufficient application of organic fertilizers enhance the natural climatic effects of degradation. The correlation coefficient between climatic factors and humus content (r=–0.81) emphasizes the dominant role of the complex influence of climate + anthropogenic factor.

For the first time in the region, a comprehensive analysis of spatio-temporal soil changes was carried out using a network of control points and laboratory data. The results obtained make it possible to quantitatively predict soil degradation and develop adaptation measures for sustainable management of agricultural landscapes.

Recommendations for soil resource management: implementation of soil organic matter conservation systems, including crop rotation with legumes and composting; application of minimal or zero tillage on slopes and in depressions to prevent compaction; monitoring of moisture supply and climate change using a network of observation points to predict degradation processes; spatially oriented planning of land use, considering relief features and the risk of dehumification.

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