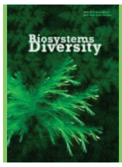
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Global climate change will lead to a decrease in the erosion resistance of Polissya and Forest-Steppe soils

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Soil erosion is an ecological process leading to both soil degradation and soil fertility reduction. The USLE empirical model incorporates the soil erosion index (K-factor), describing the susceptibility to soil erosion, which depends on the structural stability of soil aggregates. The article evaluates the spatial variability of the erodibility factor across Polissya and the Forest-Steppe regions of Ukraine and forecasts the changes in this indicator in the near-, medium- and long-term. The assessment of the soil erodibility factor K for the period 1970–2000 suggests that this indicator was at the level of 0.11 ± 0.013 t•ha•h•/ (ha•MJ•mm). The organic matter content is an important factor determining the soil's sensitivity to erosion. The highest stocks of organic matter in the region were observed in the northern part of the territory, due to the accumulation of organic matter caused by waterlogging of soils and extensive swamping processes. In agricultural areas, relatively low soil organic matter content was observed in some landscapes in the centre, south and west. The dependence of soil organic matter content on bioclimatic variables was established to predict the trend of changes in the soil erodibility factor K over time due to global climate change. Regression analysis was able to explain 79% of the variation in soil organic matter content. The statistically significant predictors of soil organic matter content were annual mean temperature, temperature seasonality, mean temperature of the wettest quarter, mean temperature of the warmest quarter, precipitation of the wettest month, precipitation of the wettest quarter, precipitation of the warmest quarter. The application of the predicted values of bioclimatic variables provided an opportunity to predict the content of organic matter in the soil and calculate the value of the soil erodibility factor K in the future. The forecast indicates that climate change is expected to result in a reduction of soil organic matter content by an average of 26.7% in 2021–2040, which would also lead to an increase in the soil erodibility factor K by 3.6%. In 2021–2040, the regional minimum organic matter content will shift from the southwest to the central part of the region. The zone of lowest erosion will decrease significantly and will be located only in the north-west of the region. The zone of highest erosion will spread in the latitudinal direction from east to west. In the period 2041–2060, climate change will not lead to significant changes in the content of organic matter in the soil, and, accordingly, the values of the soil erodibility factor K will not change significantly. The regional minimum of soil organic matter content will be observed in the southeast, and the regional maxima of soil organic matter content will be observed in the northeast and southwest. The regional minimum of soil erosion will remain virtually unchanged in the north-west of the region. In the period 2061–2080, climate change will also worsen the situation, and compared to 2041–2060, the organic matter content in the soil will decrease by 15.1%, resulting in a 1.6% increase in the soil erodibility factor K. The regional minimum of organic matter content will shift to the north and north-east. The regional maximum of soil erosion will spread in space. The differential approach allowed us to better reflect the trends in soil erosion. In the period from 1970–2000 to 2021–2040, the largest increase in soil erosion will occur in the north of the region. A decrease in erosion will occur in the south-west of the region. In the following period, the area of increased soil erosion will be localised in the east of the region. In the period up to 2061–2080, the area of increased soil erosion will cover the north and south-west of the region. Soil organic matter stock is a risk factor for increased soil sensitivity to erosion in the sense that a larger stock can be reduced to a greater extent. Thus, in the coming decades, the Polissia region should be considered the most risky in the context of the negative effects of climate change on soil erosion resistance. In the medium term, the deterioration trend will continue in the northeast of Polissia, and in the long term, threats will resume throughout Polissia.

Keywords: climate change; spatial pattern; temporal dynamic; landscape; soil cover.

Introduction

Soil erosion represents an ecological process leading to both soil degradation (Bridges & Oldeman, 1999) and soil fertility loss (Pimentel & Burgess, 2013). The erosion leaches nutrients from the soil, reduces the water-holding capacity of soils, and is a factor in reducing crop yields. Water erosion causes annual global production of corn and wheat to decline by 8.9 million tonnes and 5.6 million tonnes, respectively, which is worth US$3.3 billion (Carr et al., 2021). Erosion as an ecological process can destabilise entire landscapes. The spatial relationship between landscape diversity and soil erosion is a factor in reducing soil erosion (Jiang et al., 2020). Empirical USLE models include six main input factors, including storm susceptibility (R-factor), soil erodibility (K-factor), length and slope (LS-factor), cover crop (C-factor), and management practices (P-factor) (Valkanou et al., 2022). The K-factor describes the susceptibility to soil erosion, which depends on the structural stability of soil aggregates (Qian et al., 2022). In turn, the structural stability of soil aggregates depends on soil texture and organic matter content (Carrizo et al., 2015). Erosion resistance has a significant impact on erosion intensity (Iaaich et al., 2016), so the K factor is used to estimate the rate of soil erosion throughout the erosion process (Wang et al., 2014). Erodibility in soils of different mechanical composition decreases with increasing organic matter content. This is explained by the fact that there is a positive correlation between the content of organic matter in the soil and the weighted average diameter of aggregates. Soil erodibility is significantly dependent on the particle size distribution. Organic matter can improve the stability of soil aggregates, which helps to reduce soil erosion (Kiani & Ghezelseflo, 2016). Soil permeability and soil structural stability are two very important characteristics that influence the soil erosion rate (Bonilla & Johnson, 2012).

There are two aspects to the study of the K-factor: different ways of experimentally assessing this indicator and mapping the K-factor. Determining soil erosion at larger spatial scales is often problematic due to the lack of spatial data on soil properties and field measurements to validate the model. As soil erosion is difficult to measure at large scales (Yang et al., 2018), soil erosion models are an important assessment tool at regional, national and European levels. Field measurements of the K-factor are expensive and often cannot be easily extended to different spatial scales, and the relationship between 'traditional' soil properties and soil erosion is often used to build spatial models (Panagos et al., 2014). The issue of predicting soil sustainability in the context of global climate change remains unexplored.

Pedotransfer functions, establishing the dependence of soil erosion resistance on other soil properties, can be adopted as a framework for predicting variations of the K-factor in the context of global climate change. Soil texture is a conservative property that depends on the bedrock. The most significant driver of changes in soil erosion resistance is the content of organic matter. Soil carbon, as an essential component of terrestrial ecosystems, plays a critical role in sustaining biodiversity and enhancing agricultural productivity (Bhattacharya et al., 2016). Soil organic carbon is being lost both through land use (Başaran et al., 2024) and global climate change (Zhao et al., 2021). Climatic factors such as temperature and precipitation can regulate soil organic carbon fluxes, affecting the production and mineralisation of organic matter and soil (Alvarez & Lavado, 1998). Climate warming can directly or indirectly affect the decomposition of soil organic matter through the control of soil microbes, enzyme activity and soil respiration (Conant et al., 2011). Warming exerts a more pronounced influence on respiration compared to photosynthesis; consequently, a warming climate may enhance the release of soil carbon into the atmosphere (Arora et al., 2013). Average annual precipitation and average annual temperature are most often considered as factors influencing soil organic carbon content (Delgado-Baquerizo et al., 2017).

Diverse biotic and abiotic factors influence the distribution and dynamics of total soil carbon, leading to accurate geospatial projections over large geographic regions that are challenging but important (Keskin et al., 2019). Bioclimatic variables are correlated with soil carbon levels, as climatic factors significantly influence soil carbon dynamics and its accumulation within terrestrial ecosystems (Zeraatpisheh et al., 2022). These variables quantify climatic factors that directly impact biological processes, and their interaction with soil properties is crucial for determining the distribution and accumulation of soil organic carbon (Tayebi et al., 2021). An understanding of the complex relationships between bioclimatic variables and soil C levels is important to unravel the complex mechanisms that govern soil C sequestration and cycling, and to predict the impacts of climate change on soil C stocks (Elbasiouny et al., 2022). Changes in temperature and precipitation can alter the balance between soil carbon supply and removal, potentially leading to changes in soil carbon stocks (Shen et al., 2016). The dynamics of bioclimatic variables over time can explain the accumulation of soil carbon in the context of global climate change (Radočaj et al., 2023).

The aim of this study is to assess the spatial variability of the erodibility factor within Polissia and the Forest-Steppe zone of Ukraine and to forecast changes in this indicator in the near-, medium- and long-term.

Materials and methods

The spatial variability of the erosion factor across ten administrative regions in northern and northwestern Ukraine was examined. This area encompasses the geographical zones of Polissia and the Forest-Steppe (Zymaroieva et al., 2019). Prior to the administrative and territorial reform in Ukraine from 2015 to 2022, environmental characteristics were averaged across the administrative districts. This methodology was employed due to the fact that the area of the 'traditional' districts is smaller and exhibits greater ecological homogeneity compared to the newly established administrative units (Zymaroieva et al., 2021). Furthermore, data on crop yields have been collected over an extended period within the 'old' administrative districts, which is essential for analyzing the relationship between productive potential and soil and landscape conditions. Information regarding the spatial variability of the region's soil cover was obtained from the Harmonised World Soil Database (Version 2.0). Soil property data were acquired from the SoilGRIDS database (www.isric.org/explore/soilgrids) utilizing the geodata package (Hijmans et al., 2024). The Revised Universal Soil Loss Equation (RUSLE) was employed to estimate annual soil loss. RUSLE was specifically designed to predict long-term average annual soil erosion. Its contemporary computer interface enhances usability and incorporates physically relevant input values that are readily accessible in existing databases or can be easily derived from Digital Elevation Models (DEMs) and satellite imagery (Kim et al., 2005). RUSLE is widely recognized as the most effective model for practical erosion prediction, making it suitable for application at both local and regional scales. Additionally, various parameters, such as slope and aspect, which can be derived from DEMs and Land Use/Land Cover (LULC) data obtained from satellite imagery, can be seamlessly integrated into the RUSLE framework (Zerihun et al., 2018). RUSLE calculates the expected average annual erosion on field slopes using the equation established by Wischmeier & Smith (1978):

$$A = R + K + LS + C + P,$$

where A represents the average spatial and temporal soil loss per unit area, typically in tonnes per hectare per year, over the time period designated for R. R is the rainfall-runoff erosion factor, including the rainfall erosion rate and additional runoff from snowmelt, expressed in megajoules per millimeter per hectare per hour per year. K quantifies soil loss per unit of erosion index for a specific soil type, measured on a standard plot of a 22.1-meter length with a uniform 9% slope in continuous clean cultivation. L is the slope length factor, indicating the ratio of soil loss from the field slope to that from a 22.1-meter slope under identical conditions. S is the slope steepness factor, showing the ratio of soil loss from the field slope gradient to that from a 9% slope under similar conditions. C, the cover management factor, compares soil loss from an area with specific cover and management practices to that from an identical area under continuous cultivated fallow. P, the practical support factor, compares soil loss with support measures like contouring or terracing to that from conventional farming. The L and S factors illustrate the effects of slope length and steepness, while the C and P factors reflect the impacts of cropping systems and erosion control measures.

The soil erodibility factor (K) serves as an indicator of a soil's or surface material's vulnerability to erosion, sediment transportability, and the volume and rate of runoff under specific rainfall conditions, measured according to standardized protocols. The standard condition involves a 22.6-meter-long unit plot with a 9% gradient that is consistently maintained. The soil erodibility factor K is estimated based on soil texture and organic carbon content. K values represent the rate of soil loss in relation to the rainfall and runoff erosion rate (R). The soil erodibility factor K is most accurately determined through direct measurements at natural runoff sites. A model that utilizes data on soil particle size and organic matter content has been developed to estimate K values (Torri et al., 1997). This model includes several parameters that are relatively straightforward to obtain. The formula employed in this model is as follows:

$$K = 0.0293 \times \left(0.65 - D_g + 0.24D_g^2\right)$$
$$\times\, exp\left(-0.0021\frac{OM}{c} - 0.00037\left(\frac{OM}{c}\right)^2 - 4.02c + 1.72c^2\right),$$

where OM is the organic matter content of the soil expressed as a percentage and c is the clay content expressed as a fraction. Dg can be calculated using the following formula:

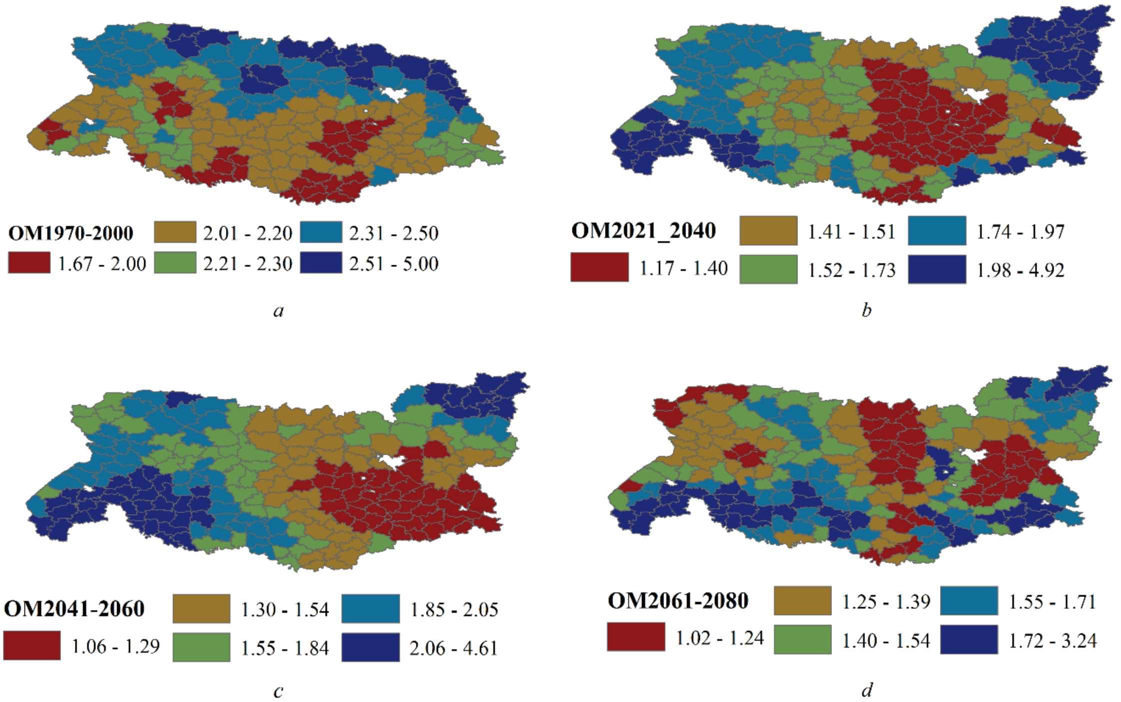
$$D_g = \sum f_i \lg\sqrt{d_i d_{i-1}},$$

where D_g is the natural logarithm of the geometric mean particle size distribution, di (mm) is the maximum diameter of the *i*-th class, d_{i-1} (mm) is the minimum diameter, and f_i is the mass fraction of the particle class of the corresponding size. D_g was calculated on the basis of three particle size classes: sand (0.05–2.00 mm), silt (0.002–0.05 mm), and clay (0.00005–0.002 mm). The resulting K values were expressed in SI units of t•ha•h•/ (ha•MJ•mm).

Results

The assessment of the soil erosion factor K for the period from 1970 to 2000 indicates that this factor averaged 0.11 ± 0.013 $(t \cdot gm^2 \cdot h) / (MJ \cdot mm \cdot h^2)$. The content of organic matter is a crucial determinant of soil sensitivity to erosion. In the region, the highest reserves of organic matter were observed in the northern part of the country, attributed to the accumulation of organic matter resulting from waterlogging and extensive hydromorphic processes (Fig. 1). In agricultural areas, relatively low soil organic matter content was found in certain landscapes in the central, southern and western regions. The relationship between soil organic matter content and bioclimatic variables was established to predict changes in soil erosion factor K over time as a result of global climate change. Regression analysis accounted for 79% of the variation in soil organic matter content (Table 1). The statistically significant predictors of soil organic matter content included mean annual temperature, seasonality of temperature, mean temperature of the wettest quarter, mean temperature of the warmest quarter, precipitation during the wettest month, precipitation during the wettest quarter and precipitation during the warmest quarter. Using the predicted values of the bioclimatic variables, it was possible to predict the soil organic matter content and calculate the future value of the soil erosion factor K (Fig. 2).

The forecast showed that climate change would lead to a decrease in soil organic matter content in the period 2021–2040 by an average of 26.7% (t = 13.6, P < 0.001), which would also lead to an increase in the soil erodibility factor K by 3.6% (t = 3.3, P = 0.002). In 2021–2040, the regional minimum organic matter content will shift from the southwest to the central part of the region. The zone of lowest erosion will significantly decrease and will be located only in the northwest of the region (Fig. 3). The zone of highest erosion will spread in the latitudinal direction from east to west.



a *b*

c *d*

Fig. 1. Spatial variation of organic carbon content (%) in soil and its forecast over time: *a* is the variability of the indicator for the period 1970–2000; *b* is the forecast of the indicator's variability for the period 2021–2040; *c* is the forecast of the indicator's variability for the period 2041–2060; *d* is the forecast of the indicator's variability for the period 2061–2080

Table 1
Multiple regression analysis of the dependence of soil organic matter content on bioclimatic variables ($R_{adj}^2 = 0.79$, F = 40.5, P < 0.001)

Bioclimatic variable	Beta regression coefficient ± standard error	Regression coefficient ± standard error	*t*(186)	*P*–value
Intercept	–	9.46 ± 18.66	0.51	0.61
Annual Mean Temperature (Bio_1)	–3.19 ± 0.43	–0.58 ± 0.08	–7.39	<0.001
Mean diurnal range (Bio_2)	–0.56 ± 1.59	–0.13 ± 0.37	–0.35	0.72
Isothermality (Bio_3)	0.61 ± 2.05	0.03 ± 0.12	0.30	0.77
Temperature seasonality (Bio_4)	–1.96 ± 0.68	0.00 ± 0.00	–2.87	<0.001
Max temperature of warmest month (Bio_5)	2.28 ± 1.78	0.22 ± 0.17	1.28	0.20
Min temperature of coldest month (Bio_6)	–1.53 ± 1.63	–0.16 ± 0.18	–0.94	0.35
Temperature annual range (Bio_7)	–1.90 ± 3.15	–9.40 ± 15.57	–0.60	0.55
Mean temperature of wettest quarter (Bio_8)	–0.29 ± 0.14	–0.02 ± 0.01	–2.07	0.04
Mean temperature of driest quarter (Bio_9)	0.12 ± 0.08	0.02 ± 0.01	1.58	0.12
Mean temperature of warmest quarter (Bio_10)	3.44 ± 0.84	0.37 ± 0.09	4.11	<0.001
Mean temperature of coldest quarter (Bio_11)	0.29 ± 0.57	0.04 ± 0.07	0.52	0.60
Annual precipitation (Bio_12_	1.16 ± 0.72	0.00 ± 0.00	1.61	0.11
Precipitation of wettest month (Bio_13)	1.17 ± 0.36	0.01 ± 0.00	3.26	<0.001
Precipitation of driest month (Bio_14)	–0.32 ± 0.21	–0.01 ± 0.01	–1.52	0.13
Precipitation seasonality (Bio_15)	–0.20 ± 0.36	0.00 ± 0.01	–0.56	0.57
Precipitation of wettest quarter (Bio_16)	3.84 ± 1.05	0.01 ± 0.00	3.65	<0.001
Precipitation of driest quarter (Bio_17)	–0.06 ± 0.41	0.00 ± 0.00	–0.16	0.88
Precipitation of warmest quarter (Bio_18)	–5.65 ± 0.94	–0.02 ± 0.00	–6.01	<0.001
Precipitation of coldest quarter (Bio_19)	–0.08 ± 0.30	0.00 ± 0.00	–0.28	0.78

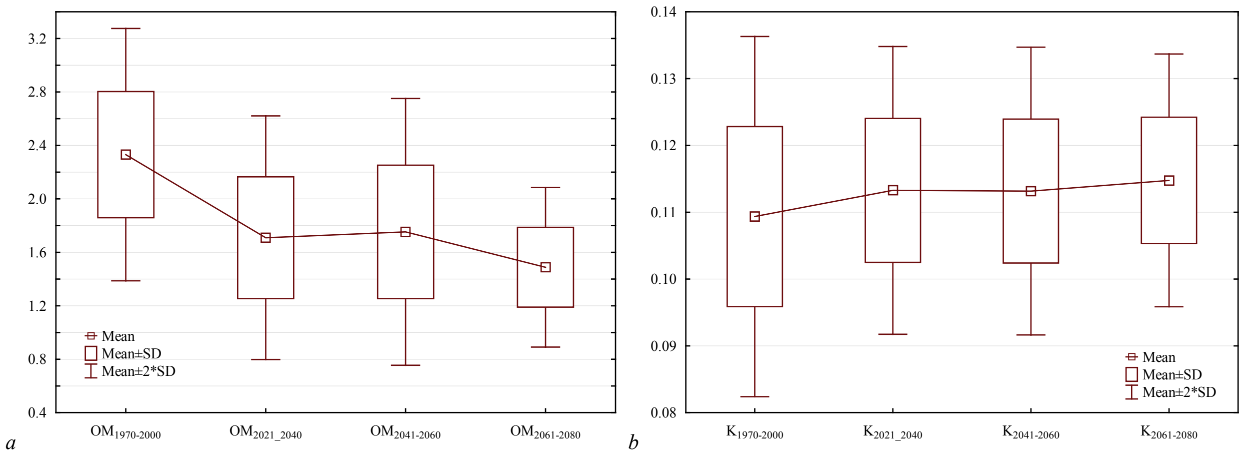


Fig. 2. Variability of organic carbon content explained by the variability of bioclimatic factors and soil erosion factor K in different time periods: abscissa is the time periods 1970–2000, 2021–2040, 2041–2060, and 2061–2080, ordinate a is the organic carbon content (%); b is the value of soil erosion factor K (t•ha•h•/ (ha•MJ•mm))

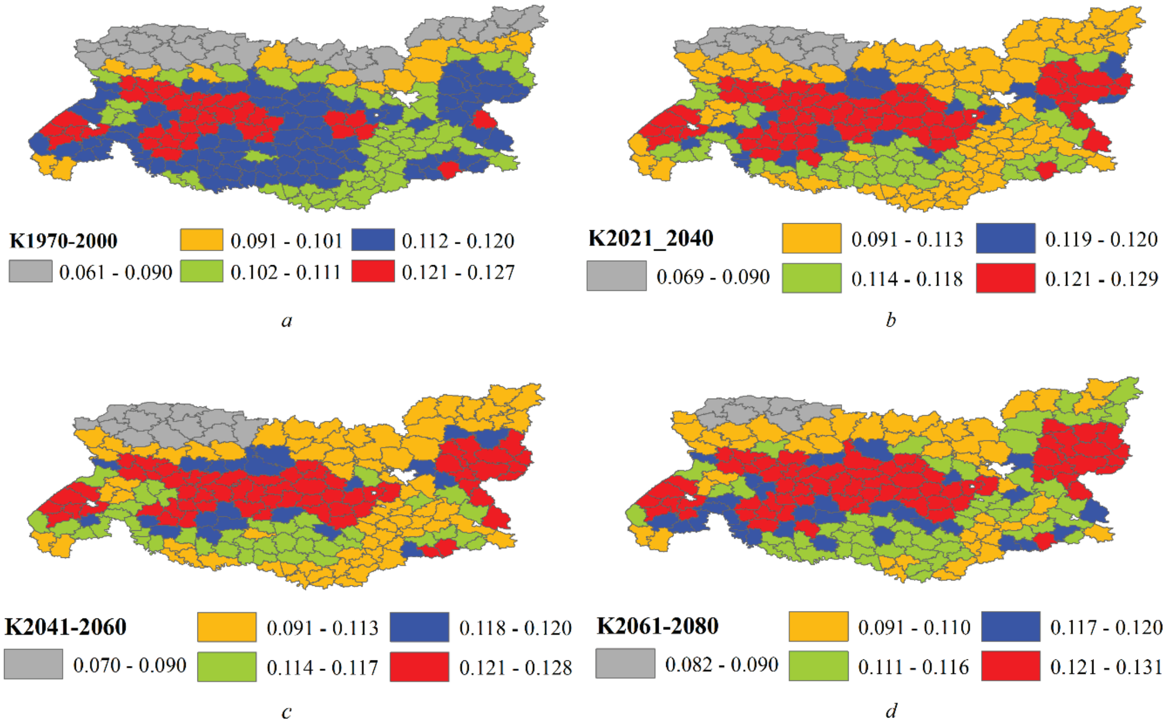


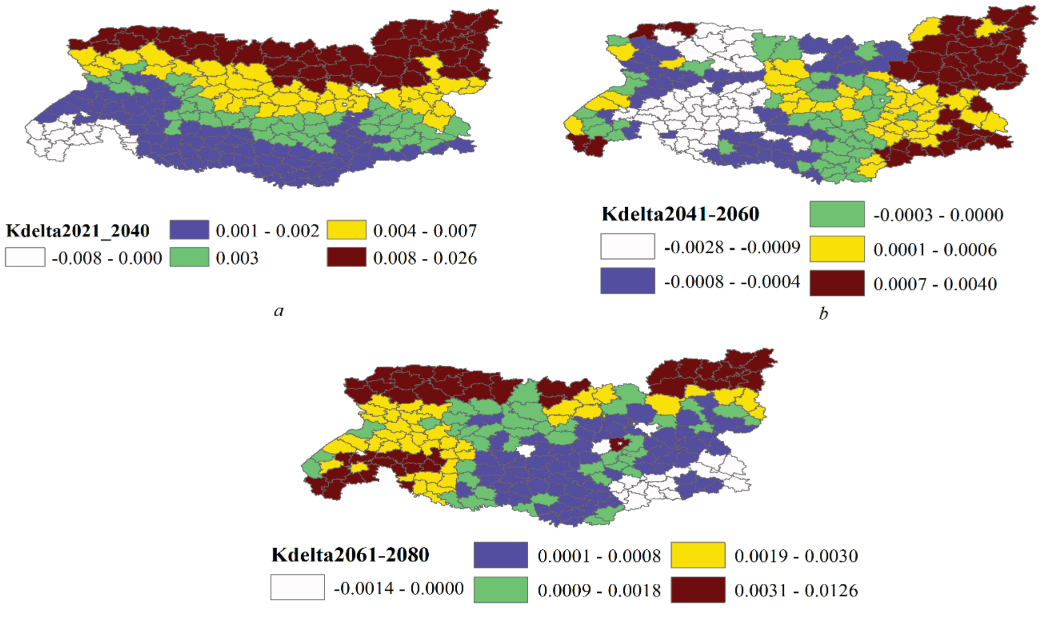
Fig. 3. Spatial variation of the soil erosion factor K (t•ha•h•/ (ha•MJ•mm)) and its forecast in time: *a* is the variability of the indicator for the period 1970–2000; *b* is the forecast of the indicator variability for the period 2021–2040; *c* is the forecast of the indicator's variability in the period 2041–2060; *d* is the forecast of the indicator's variability in the period 2061–2080

The climate change in the period 2041–2060 will not lead to significant changes in soil organic matter content ($t = 0.92$, $P = 0.36$), and, accordingly, the values of the soil erosion factor K will not change significantly ($t = 0.099$, $P = 0.92$). The regional minimum of soil organic matter content will be observed in the southeast, and the regional maximums of soil organic matter content will be observed in the northeast and southwest. The regional minimum of soil erosion will remain virtually unchanged in the north-west of the region. In the period 2061–2080, climate change will also worsen the situation and, compared to 2041–2060, the organic matter content in the soil will decrease by 15.1% ($t = 6.5$, $P < 0.001$), resulting in an increase in the soil erosion factor K by 1.6% ($t = 1.9$, $P = 0.05$). The regional minimum of organic matter content will shift to the north and northeast. The regional maximum of soil erosion will spread in space.

The differential approach allowed us to better reflect the trends in soil erosion (Fig. 4). In the period from 1970–2000 to 2021–2040, the largest increase in soil erosion will occur in the north of the region. A decrease in erosion will occur in the south-west of the region. In the following period, the area of increased soil erosion will be localised in the east of the region. In the period up to 2061–2080, the area of increased soil erosion will cover the north and south-west of the region. The stock of organic matter in the soil is a risk factor for increasing soil sensitivity to erosion in the sense that a larger stock can be reduced by a greater level (Table 2). Clay and silt are factors that stabilise erosion risks, while sand content, on the other hand, increases the risk of increasing soil sensitivity to erosion. Obviously, forest ecosystems are associated with sandy soils, where the risk of increasing soil erosion sensitivity is higher, which explains the positive correlation between the proportion of forest ecosystems in the landscape cover structure and the risk of increasing the soil erosion factor K.

Discussion

The estimate of the soil erosion factor K in the study region was 0.11 ± 0.013 t•ha•h•/ (ha•MJ•mm), which is almost three times higher than the estimate for Europe as a whole. The K erosion factor in the USA varies between 0.7 for the most vulnerable soils, 0.3 for moderate vulnerability and 0.02 for the most resilient soils. In Africa, the erosion factor K varies from 0.01 to 0.3 (Panagos et al., 2014). The distribution of terrestrial soil organic carbon varies according to climate and soil conditions. Effective spatial land cover forecasting models are essential for making informed decisions in land management and climate change mitigation (Taylor et al., 2023). Predicting changes in the erosion factor, we assumed that the most significant driver of changes in this indicator is the organic content of the soil, while soil texture is a rather conservative indicator (Chen et al., 2023). However, it cannot be stated that the texture factor does not affect the temporal dynamics of soil resistance to erosion. Soil erosion can lead to the destruction and redeposition of topsoil, which can affect its particle size distribution and, consequently, resistance to further erosion (Berhe & Torn, 2017). It should be noted that such patterns are unlikely to have a significant impact at the spatial level, which covers administrative districts. Soil carbon stocks are largely controlled by climate and vegetation cover (Yorkina et al., 2022), and these major factors, especially land use patterns, are changing rapidly under the influence of human activities (Yigini & Panagos, 2016).



a

b

c

Fig. 4. Spatial variability of the increase in the soil erosion factor K in successive time periods:
a in the period from 1970–2000 to 2021–2040; *b* in the period from 2021–2040 to 2041–2060; *c* in the period from 2041–2060 to 2061–2080

Table 2
Correlation of soil properties and landscape cover types with increases in the soil erosion factor K in successive time periods (correlation coefficients are shown, which are statistically significant for $P < 0.05$)

Variable	Successive periods		
	from 1970–2000 to 2021–2040	from 2021–2040 to 2041–2060	from 2041–2060 to 2061–2080
OM	0.17	0.20	0.49
Clay	–0.78	–0.16	–0.65
Sand	0.71	–	0.67
Silt	–0.57	–	–0.60
Rainfed croplands	–0.57	–	–0.60
Mosaic Croplands/Vegetation	–	–	–0.33
Mosaic Vegetation/Croplands	–0.36	0.17	–0.24
Closed broadleaved deciduous forest	0.21	–	0.61
Closed needleleaved evergreen forest	0.41	–	0.21
Open needleleaved deciduous or evergreen forest	0.69	0.25	0.51
Closed to open mixed broadleaved and needleleaved forest	0.56	–	0.49
Mosaic Grassland/Forest–Shrubland	–0.28	–0.16	0.14
Closed to open grassland	–0.17	–	–
Sparse vegetation	–0.30	–	–0.37
Closed to open vegetation regularly flooded	0.16	–	0.15
Artificial areas	–	–	–
Water bodies	–	–	–0.17

The organic matter content of soil is largely dependent on climatic conditions, which can be modelled by bioclimatic variables (Zhukov et al., 2017). Our model is not a process model, but a simulation model. For example, an increase in solar energy reaching the Earth's surface is a factor in accelerating soil formation and accumulation of organic matter in the soil. However, the model shows that the average annual temperature is a predictor with a negative regression coefficient. This result is explained by the fact that in northern regions with lower average annual temperatures, organic matter accumulates more due to the development of waterlogging processes as a result of excessive landscape moisture (Kunakh et al., 2023). The soil carbon pool is largely controlled by climate change and soil water dynamics (Zhao et al., 2018). The developed model is used to predict changes in soil organic matter content due to climate change. Temperature rise as a consequence of global climate change can be considered as a real driver of organic matter decline in marshland due to increased moisture evaporation, lower water levels in reservoirs, and increased oxidation of organic matter due to the availability of atmospheric oxygen. These results are in line with findings that indicate that the combination of lowering groundwater levels through artificial drainage and climate warming has a significant impact on soil carbon storage (Bian et al., 2020).

The northern regions of the study area are characterised by high levels of organic matter in the soil due to the development of waterlogging and slower mineralisation of organic matter under anaerobic conditions due to excess moisture. In the northern regions, organic matter accumulates in the organogenic layer of the soil under conditions of acidic and very acidic soil solution reaction. The central and southern regions have a lower organic matter content, but organic matter accumulates in the mineral layers of the soil. It is worth noting the high role of organic matter in the formation of soil aggregate structure, which is a factor in the high fertility of such soils (Zhukov et al., 2022). Spatial variability in soil organic matter content can be explained by bioclimatic variables. The link between climate and soil properties suggests that it is possible to predict changes in soil organic matter content due to climate change. Such models assume an almost deterministic relationship between climate conditions and soil properties, which is not true. Soil as a system has a certain level of resilience to climate variability (Jiménez-González et al., 2020), which is why changes in soil properties may lag behind climate change (Yakovenko et al., 2023). The response of the soil system may not even be monotonic: soil properties may not respond to climate change for some time. The proposed models allow us to forecast general trends in change, which makes it possible to assess the level of threats to be expected in connection with future responses. A review of the processual mechanisms of climate impact on organic matter content suggests that temperature and humidity have a rather strong influence on the processes of organic matter production, humification and mineralisation, which suggests that the lag between climate change and changes in soil organic matter content should not be significant, and the predictive power of regression models is quite strong.

The average annual temperature is a proxy for the radiation balance of the territory (Naserikia et al., 2023), which positively affects the rate of soil formation processes and contributes to the accumulateon of organic matter in the soil (Dosseto et al., 2011). Our results indicate that the negative regression coefficient indicating the effect of mean annual temperature on soil organic matter content is the result of a spatial pattern of increasing organic matter content in the north. The reason for this increase is excessive soil moisture and aerobic conditions that slow down the decomposition of organic matter (Tolunay et al., 2024). This explains the forecast of a decrease in soil organic matter content in the northern regions, as deteriorating moisture conditions due to an increase in average annual temperature will negatively affect the dynamics of organic matter (Koshelev et al., 2021). The forecasted decrease in organic matter in the southern regions can be explained by the predominant stimulation of organic matter mineralisation processes by the increase in temperature, which will outpace organic matter production processes in response to warming.

An increase in the average temperature of the warmest quarter stimulates an increase in the content of organic matter in the soil. This result underlines the particular importance of the biotic component in soil formation processes, which are most active in the warmest period of the year. Another factor that positively affects the growth of soil organic matter content is the amount of precipitation in the wettest month. This aspect of the relationship indicates the particular importance of the stability of phenological events for stabilising organic matter accumulation. Deviations from the typical course of phenological processes have a negative impact on the processes of creation and accumulation of organic matter in the soil. Our results are in line with the findings that precipitation, temperature, and leaf area index are the main contributors to changes in soil organic carbon among environmental factors (Chen et al., 2023).

A decrease in soil organic matter content is a common prediction in the context of global climate change. Spatial patterns of changes in organic matter content are more complex. Typical zonal differentiation will be disrupted, and pockets of lower organic matter content may spread to the northern regions of the study area. Such changes may include mechanisms to accelerate the projected changes, including fires. Droughts are a factor in increasing the risk of forest fires, the obvious consequence of which is a decrease in the accumulation of organic matter in the ecosystem as a whole and in the soil in particular. Both the destruction of vegetation cover and a decrease in soil organic matter content significantly reduce the soil's erosion resistance.

The results suggest that the current zone of significant soil erosion risk is already covering the area of the largest agricultural development. The northern regions are protected by forest vegetation. The forecast indicates significant risks of reduced soil resilience to precipitation in the north and northeast in the coming decades. These prospects are worrisome and point to the need to focus on preserving forest ecosystems and developing measures to maintain the water regime in the northern territories. While in the previous period of time, drainage was the main area of land reclamation in Polissya, in the near future it is necessary to develop tools to stabilise moisture conditions. Such tools should include both hydraulic engineering measures and measures to protect natural complexes. Preserving swamps and rivers, preventing excessive ploughing of catchment areas, and preserving forest cover in floodplains should be the main guidelines of government policy to prevent erosion losses. Thus, in the coming decades, the Polissia region should be considered the most risky in the context of the negative effects of climate change on soil erosion resistance. In the medium term, the deterioration trend will continue in the northeast of Polissia, and in the long term, threats will resume throughout Polissia.

In the Forest-Steppe zone, deterioration risks can be foreseen in the southeast of the region in the medium term, and in the long term, threats can be predicted in the southwest of the region. The design of erosion control measures should also take into account the lag in their implementation and the delay in achieving the planned results of the measures. Therefore, the medium- and long-term prospects for negative changes do not look so encouraging, and if we take into account the possibility of accelerating negative consequences due to the inclusion of processes that have not yet manifested themselves, the overall context clearly requires urgent management decisions.

Conclusion

The soil erosion factor is an important indicator for assessing the overall level of water erosion of soils. The spatial and temporal modelling of the variability of this indicator was carried out on the basis of a pedotransfer function that links the erosion factor to the content of granulometric fractions and soil organic matter. This relationship is convenient for calculation, as the input indicators are presented in the form of spatial data layers. The relationship also indicates the main areas of landscape management for erosion control. The estimate of the soil erosion factor K in the studied region was 0.11 ± 0.013 t•ha•h/(ha•MJ•mm). Prediction of time variability of soil organic matter content allowed us to predict the spatial variability of the erosion factor in the future. The forecasts indicate a particular risk of worsening water erosion risks in Polissia. In the medium and long term, the risks of increased erosion are predicted for the Forest-Steppe zone of Ukraine.

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