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Estimation and forecasting of soil losses from water erosion in the Polissia and Forest Steppe of Ukraine

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Abstract. Global warming and changes in land use are considered the main drivers of future soil-erosion dynamics and therefore require attention. We modelled the possible impacts of climate change and land use change on soil erosion rates in the Polissia and Forest-Steppe lands of Ukraine up to 2060. The final water-erosion rate depends on the amount and rhythm of precipitation during the year, the ability of the soil to withstand the erosive effects of precipitation, and the protective effect of vegetation cover. The variability of the observed and predicted RUSLE parameters over time demonstrated a linear trend in dependence on time over the 100 years from 1960 to 2060. The slope of the linear model indicates the direction and strength of the time trend in the variability of a relevant parameter. In 52.9% of the cases, the R-factor showed a decreasing trend over time. The zone of reduced intensity of the erosive impact of precipitation has a clear geographical distribution. In the southern, central, and to a lesser extent in the eastern part of the region, the erosive impact of precipitation will decrease in 1960–2060. In the north and southwest, there will be no significant changes in the intensity of the precipitation erosion over time. In the northeast and west of the region, the intensity of precipitation-induced erosion will increase over time. The K-factor will not change over time only in 1% of the cases. In other cases, the trend of changes in this indicator will be positive, indicating a monotonous decrease in the ability of the soil cover to withstand the erosive effects of precipitation. The least negative changes will occur in the southeast. In the north and especially in the northeast, the decrease in the soil's ability to resist erosion will be the greatest. The C-factor indicates the ability of the vegetation cover to resist water erosion. In 14.6% of the cases, this indicator will decrease over time, suggesting a strengthening in the protective capacity of the vegetation cover. This increase will occur in the southwest of the region. In the north and east of the region, the C-factor will elevate monotonically over time, indicating a decrease in the protective capacity of the vegetation cover. The water erosion score is a multiplicative indicator of all these factors. The model shows that both an upward trend in water erosion and a downward trend in soil erosion will be observed within the study area. In 35% of the cases, soil erosion will decrease. The zone of reduced erosion intensity is predicted in the centre and south of the region. Accordingly, in 65% of the cases, soil erosion will increase, most notably in the east and southeast of the region. In the northwest, the increase in erosion intensity will be moderate. The regression analysis shows that the trends in factors R, K, and C together can explain 65.1% of the variability in the water erosion trend. Factor K was the largest contributor to the erosion trend and was able to explain 26.3% of the variability in the water erosion trend. The R factor was able to explain 19.9% of the variability in the water erosion trend, and the C factor explained 18.9%.

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

Introduction

Soil, a non-renewable resource, is vital to the Earth's ecosystem, as it supports approximately 95% of global food production and provides essential services such as biomass production and pollutant filtration. Unsustainable management and climate change threaten soil natural capital. Soil formation is a slow process, taking centuries to millennia, influenced by parent rock composition, climate, organisms, and time. Accelerated erosion, which exceeds the natural soil formation rates, leads to the loss of fertile topsoil, reducing soil depth, and impacting vegetation and land use (Alewell et al., 2015). The European Commission's *Soil Thematic Strategy* identifies soil erosion as a principal threat (Panagos et al., 2024), with significant implications for sustainability, climate change, and human wellbeing. Effective policies and sustainable practices offer the EU a chance to protect soil resources for future generations (Panagos et al., 2016). In the past decade, soil erosion has emerged as a major concern in the EU, affecting food production, water quality, ecosystem services, and biodiversity. Water erosion is the primary cause of soil loss in Europe (Ferreira et al., 2022), influenced by precipitation, soil type, topography, land use, and management practices. It significantly impacts the agricultural productivity, ecosystem stability, and water quality. This process involves the detachment, transportation, and deposition of soil particles by rainfall and surface runoff, leading to the degradation of fertile topsoil. Europe's diverse landscapes, ranging from mountainous regions to plains, contribute to varying erosion intensities, with areas of steep slopes, intense rainfall, and improper land management practices being the most vulnerable. Agricultural activities exacerbate water erosion, particularly in regions where monocropping, overgrazing, or improper tillage practices leave soils exposed to heavy rains. The Mediterranean region, for instance, experiences severe water erosion due to its intense rainfall events, steep terrain, and sparse vegetation (Hag Husein et al., 2024). By contrast, Northern and Central Europe face erosion risks primarily on agricultural lands during seasonal snowmelt or prolonged wet periods. Forested areas, which typically protect from erosion, have also been affected by deforestation and logging activities, further increasing the susceptibility of soils to water erosion. The consequences of water erosion are far-reaching. The loss of fertile topsoil reduces agricultural yields, requiring greater reliance on fertilizers, which can lead to eutrophication of nearby water bodies. Sediment runoff clogs waterways, impacting aquatic ecosystems and increasing the risk of flooding. Moreover, water erosion contributes to the decline in carbon sequestration potential, as eroded soils release stored carbon into the atmosphere, exacerbating the climate change.

Efforts to mitigate water erosion in Europe include implementing sustainable agricultural practices such as contour farming, cover cropping, and conservation tillage. Reforestation and the establishment of buffer strips along waterways help stabilize soils and reduce sediment transport. Policymakers and researchers are also leveraging advanced tools, such as GIS and remote sensing, to monitor erosion patterns and identify high-risk areas. The European Union's initiatives, including the *Soil Thematic Strategy* and the *Common Agricultural Policy*, aim to address soil erosion through regulatory frameworks and financial support for sustainable land management practices. Despite these efforts, water erosion remains a significant challenge in Europe, requiring continuous collaboration among governments, scientists, and land managers to protect soil resources and ensure long-term environmental and economic sustainability. An increase in the global average surface temperature compared with pre-industrial levels could significantly affect desertification, land degradation, and food security (Bolan et al., 2024). Desertification, caused by human activities, degrades land in arid and semi-arid regions, reducing biological productivity and converting agricultural land into desert (Karrar & Stiles, 1984). Climate change exacerbates land degradation through soil erosion, loss of vegetation, forest fires, and thawing permafrost (Agbeshie et al., 2022). This degradation leads to the loss of soil functions, threatening food production and human survival, as soil is often viewed as a non-renewable resource (Kraamwinkel et al., 2021). Climate change also causes volatile crop yields and food supplies, resulting in widespread food insecurity and malnutrition (Mirzabaev et al., 2023). Additionally, global warming intensifies the hydrological cycle, increasing precipitation and the frequency of extreme weather events like floods and droughts (Brooks, 2013). These changes impact soil functions and directly affect crops, making soil moisture a critical factor for the global food security (Furtak & Wolińska, 2023).

Changes in precipitation, temperature, solar radiation, and atmospheric carbon dioxide are expected to accelerate the soil erosion rates. Reduced annual precipitation may increase the susceptibility to erosion due to decreased phytomass production (Nearing et al., 2004). The RUSLE GIS model effectively assesses global soil erosion potential. Global warming could heighten erosion risks, especially in regions with rising precipitation and population (Yang et al., 2003). Evaluating soil loss at regional and national levels quantifies its impacts, assesses climate and land use changes, and prioritizes restoration programs (Lu et al., 2003). In Europe, studies suggest that rainfall erosion may increase, leading to greater soil loss from agricultural fields, even with decreased average annual precipitation (Routschek et al., 2014). While climate change primarily drives soil erosion, land use and crop rotation changes also contribute significantly. Converting natural vegetation to agricultural land and intensifying agricultural practices correlate with increased erosion rates (Vanwalleghem et al., 2017). Recognizing climate and land use changes as primary drivers of future soil erosion dynamics highlights the need for further research. This study aims to model the potential impacts of these changes on soil erosion rates in Ukraine's Polissia and Forest-Steppe regions by 2060.

Materials and methods

The RUSLE2015 model, based on the Revised Universal Soil Loss Equation (RUSLE) developed by Renard et al. (1997), is a widely used tool for estimating the average annual soil loss caused by water erosion on a spatial scale. It integrates multiple environmental factors to quantify soil loss rates and assess erosion risks, making it an essential model for soil conservation planning and land management strategies. This study used a modified RUSLE2015 model (Renard et al., 1997), to calculate the average annual soil loss from sheet and gully erosion with the following equation:

$$A = R \times K \times LS \times C \times P,$$

where A is the average annual soil loss (t/ha*year), R is the rainfall erosion coefficient (MJ mm/(ha*h*year)), K is the soil-erosion susceptibility coefficient (t/(ha*MJ*mm)), C is the cover management coefficient (dimensionless), LS is the slope length and steepness coefficient (dimensionless), and P is the maintenance practice coefficient (dimensionless).

The RUSLE2015 model incorporates advancements in data availability and computational tools, including the use of high-resolution geospatial data and satellite imagery. This enhances its ability to estimate soil loss across varied landscapes with greater accuracy. It also allows for the integration of land-use and land-cover data, enhancing our understanding of how human activities and management practices impact erosion rates. By calculating the spatial distribution of soil loss, RUSLE2015 helps identify erosion-prone areas, prioritize soil conservation efforts, and evaluate the effectiveness of implemented practices. The model has been widely applied in regions with diverse climates and topographies, including agricultural landscapes, forested areas, and urban settings. However, while RUSLE2015 is a robust tool, its accuracy depends on the quality and resolution of input data. Limitations include potential underestimation or overestimation of soil loss in areas with complex hydrological and geomorphological conditions. Calibration and validation with field data are essential to ensure reliable results. In conclusion, the RUSLE2015 model is a powerful framework for estimating average annual soil loss and guiding soil conservation strategies. By integrating environmental factors and leveraging modern geospatial technologies, it provides critical insights for sustainable land management and erosion control. The RUSLE2015 model enhances soil loss factors using the latest European-scale data. Unlike previous studies (Bosco et al., 2015), this research features improved input layers, transparently evaluated. Estimations for soil erosion, rainfall erosion, cover management, topographic factors, and maintenance practices were made in accordance with European Soil Data Centre guidelines (Panagos et al., 2012). The RUSLE2015 model employed the most recent freely available datasets for these estimations.

Results

The final water erosion of the soil depends on the power and rhythm of precipitation during the year, the ability of the soil to withstand the erosive effects of precipitation, and the protective effect of vegetation cover. The variability of the observed and predicted RUSLE parameters over time demonstrated a linear trend in dependence on time over the 100 years from 1960 to 2060. The slope of the linear model indicates the direction and strength of the time trend in the variability of a relevant parameter (Fig. 1). In 52.9% of the cases, the R-factor showed a downward trend over time. The zone of reduced intensity of erosive impact of precipitation has a clear geographical distribution. In the southern, central, and to a lesser extent in the eastern part of the region, the precipitation erosion will decrease during 1960–2060. In the north and southwest, there will be no significant changes in the intensity of the erosive impact of precipitation over time. In the northeast and west of the region, the intensity of the precipitation erosion will increase over time.

The K-factor will not change over time only in 1% of the cases. In other cases, the trend of changes in this indicator will be positive, indicating a monotonous decrease in the ability of the soil cover to withstand the erosive effects of precipitation. The least negative changes will occur in the southeast. In the north and especially in the northeast, the decrease in the soil's ability to resist erosion will be the greatest. The C-factor indicates the ability of the vegetation cover to resist water erosion. In 14.6% of cases, this indicator will decrease over time, indicating an increase in the protective capacity of the vegetation cover. This increase will occur in the southwest of the region. In the north and east of the region, the C-factor will increase monotonically over time, suggesting a decline in the protective capacity of the vegetation cover.

The water erosion score is a multiplicative indicator of all these factors. The model indicates that both an upward trend in water erosion and a downward trend in soil erosion will be observed within the study area. In 35% of the cases, soil erosion will decrease. The zone of decreased erosion intensity will be located in the centre and south of the region. Accordingly, in 65% of the cases, soil erosion will increase. The most significant increase in soil erosion will occur in the east and southeast of the region. In the northwest, the increase in erosion intensity will be moderate. The regression analysis shows that the trends in factors R, K, and C together can explain 65.1% of the variability in the water erosion trend ($F = 124.3$, $P < 0.001$). Factor K is the largest contributor to the erosion trend, able to explain 26.3% of its variability. Factors R and C were able to explain 19.9% and 18.9% of the variability in the water erosion trend, respectively.

In the period from 1960 to 1980, soil losses due to water erosion were 2.3 ± 2.7 t/ (ha*yr) and in 95% of the cases were ranged 0.2 to 10.0 t/(ha*yr) (Fig. 2). The highest level of erosion was typical for the south of the region. Between 1981 to 2000, the soil losses due to water erosion were 2.4 ± 2.5 t/(ha*yr) and in 95% of the cases ranged 0.3 to 9.3 t/(ha*yr). The differences with the previous period were statistically significant according to the Wilcoxon matched pairs test ($Z = 3.2$, $P = 0.002$). In the period from 2001 to 2020, the soil losses due to water erosion were 2.6 ± 2.3 t/(ha*yr), ranging 0.4 to 9.5 t/(ha*yr) in 95% of the cases. The differences with the previous period were statistically significant according to the Wilcoxon matched pairs test ($Z = 4.5$, $P < 0.001$). In the period from 2021 to 2040, the projected soil losses due to water erosion are estimated to be 2.7 ± 2.3 t/(ha*yr), with 95% of the cases expected to fall within the range of 0.5 to 10.0 t/(ha*yr).

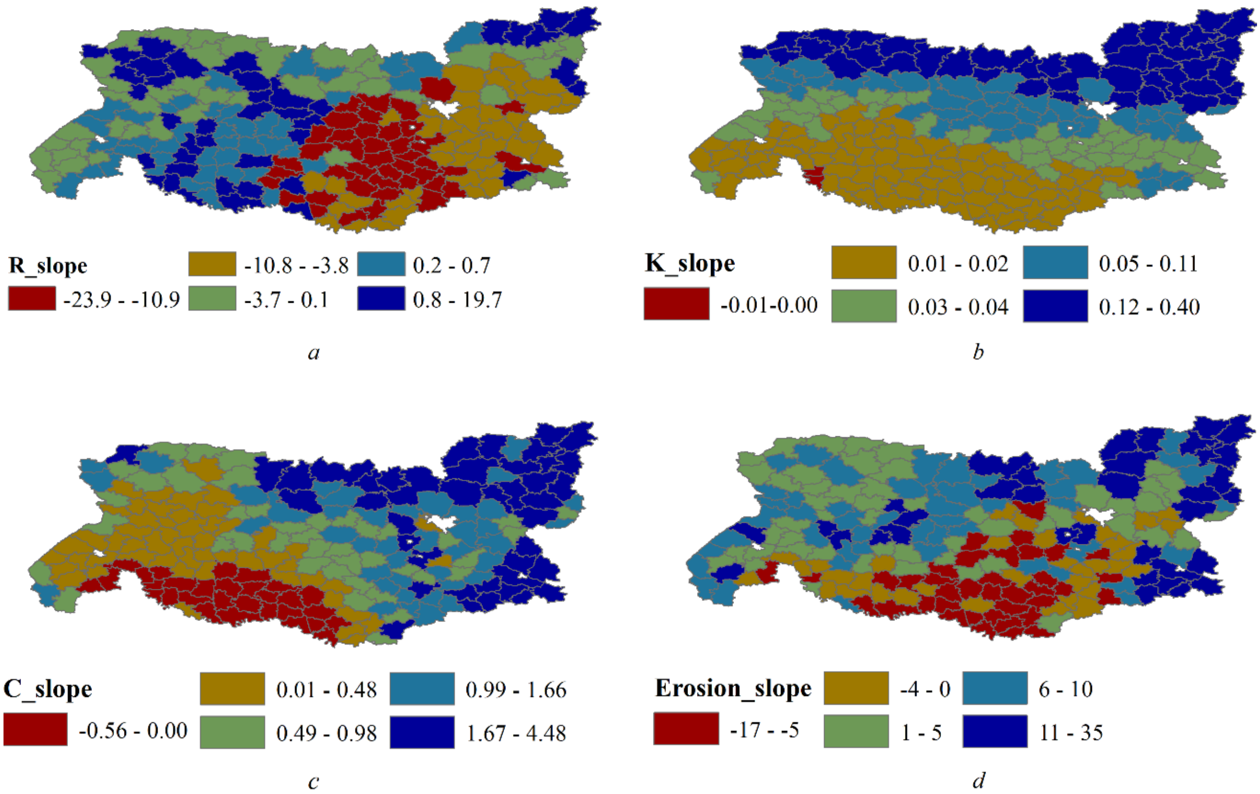

Fig. 1. Trends in water erosion factors during 1960–2060: the coefficient of linear regression for water erosion factors in relation to time is presented

The differences with the previous period are statistically significant according to the Wilcoxon matched pairs test (Z = 3.4, P < 0.001). In the period from 2041 to 2060, soil loss due to water erosion are estimated to be 2.8 ± 2.1 t/(ha*yr), ranging 0.6 to 9.4 t/(ha*yr) in 95% of the cases. The differences with the previous period are statistically significant according to the Wilcoxon matched pairs test (Z = 3.6, P < 0.001). The analysis of erosion intensity distributions across different time ranges shows that the main mechanism for the increase in erosion in the range of 2–4 t/(ha*yr) is the decrease in the occurrence of low levels of erosion in the range of 0–2 t/(ha*yr) (Fig. 3).

Discussion

The observed levels of water erosion in the Polissia and Forest-Steppe of Ukraine are at the level of 2.4–2.6 t/(ha*yr). These figures are in line with the estimates for the EU. The average annual rate of soil loss due to water erosion in the EU for the base year 2010 was 2.46 t/(ha*yr) (Panagos et al., 2015). The climate projections indicated that the hydrological cycle may intensify, leading to a 30% to 66% increase in global water erosion (Borrelli et al., 2020). Global climate change has been intensifying the soil erosion in the Ukraine's Polissia and Forest-Steppe regions since the late 20th century. The orojections indicated that water erosion will rise in the coming decades, with Europe facing an average increase of 13.0–22.5% in soil erosion rates (Panagos et al., 2021). Our projection is more moderate and ranges 3.0–6.5% compared with the current state. In the European projection, land-use change will contribute to a reduction in erosion, and increased precipitation will be the most significant factor in the growth of water erosion. In our projection, the largest contribution to the growth of water erosion is made by changes in soil erosion resistance due to a decrease in organic matter content. Changes in the rhythm of precipitation vary. In some regions, precipitation will accelerate erosion, while in others erosion may even decrease due to reduced precipitation. Changes in the ability of vegetation cover to resist erosion will have negative consequences due to climate-change-induced trends in vegetation density. Changing land use types can be recommended as an effective tool to counteract soil erosion. Reducing the area of agricultural land and increasing the area of meadow and forest vegetation is the main direction of the strategy to counteract land degradation in the region.

Changing types of land use can be recommended as an effective tool to mitigate soil erosion by adapting land management practices to reduce the vulnerability of soils to water and wind forces. Land use changes, such as transitioning from intensive agriculture to sustainable farming systems, reforestation, or implementing agroforestry, can significantly enhance soil stability and minimize erosion rates. These changes address the root causes of soil degradation by improving vegetation cover, reducing surface runoff, and enhancing soil structure. One of the most effective strategies is converting marginal agricultural lands prone to erosion into forests or grasslands. Forested areas provide dense vegetation cover that protects the soil surface from raindrop impact and slows down the surface water flow, reducing the risk of erosion. Similarly, grasslands with their extensive root systems improve the soil cohesion and enhance water infiltration, further preventing soil loss. Introducing agroforestry systems, where trees and shrubs are integrated with crops or pastures, is another effective land use modification. This approach not only reduces soil erosion through increased vegetative cover but also provides additional benefits such as improved biodiversity, carbon sequestration, and diversified income sources for farmers. For example, contour planting of trees and crops on sloping lands stabilizes soils and reduces water runoff.

In agricultural regions, changing cropping systems and adopting conservation tillage can also mitigate erosion. Practices such as crop rotation, cover cropping, and no-till farming maintain continuous soil cover, reducing the exposure of bare soil to erosive forces. Additionally, establishing buffer strips and riparian zones along water bodies contributes to trapping sediments and preventing soil from being carried into streams and rivers. Urban land use changes, such as converting impervious surfaces into green spaces or introducing permeable pavements, also play a role in controlling soil erosion. These measures reduce surface runoff during heavy rains, which is a major contributor to urban soil loss. To implement effective land use changes, it is essential to consider local environmental conditions, land suitability, and socioeconomic factors. Policies and incentives, such as subsidies for sustainable land management or payments for ecosystem services, can encourage landowners and farmers to adopt erosion-resistant practices. Monitoring and evaluation are also crucial to assess the effectiveness of land use changes and make necessary adjustments over time. Overall, changing land use types provides a flexible and sustainable solution to counteract soil erosion, contributing to soil conservation, enhanced ecosystem services, and long-term land productivity.

The predicted changes in the level of erosion are uneven across the study area. In the south of the region, a decrease in erosion intensity can be expected. This is obviously due to a significant reduction in precipitation and its erosive impact in the area. However, this forecast is not optimistic. Firstly, the southern and central parts are already experiencing the greatest impact of agriculture, which has led to very high absolute estimates of current soil erosion. Therefore, this area is in need of active measures to alleviate soil erosion as of today. Secondly, the decrease in precipitation may indicate a significant risk of desertification and the associated increase in wind erosion activity. It should be noted that climate-change predictive models are not effectve enough in simulating extreme weather events that significantly contribute to soil erosion. Therefore, it is possible that the forecasted reduction in erosion may be too optimistic.

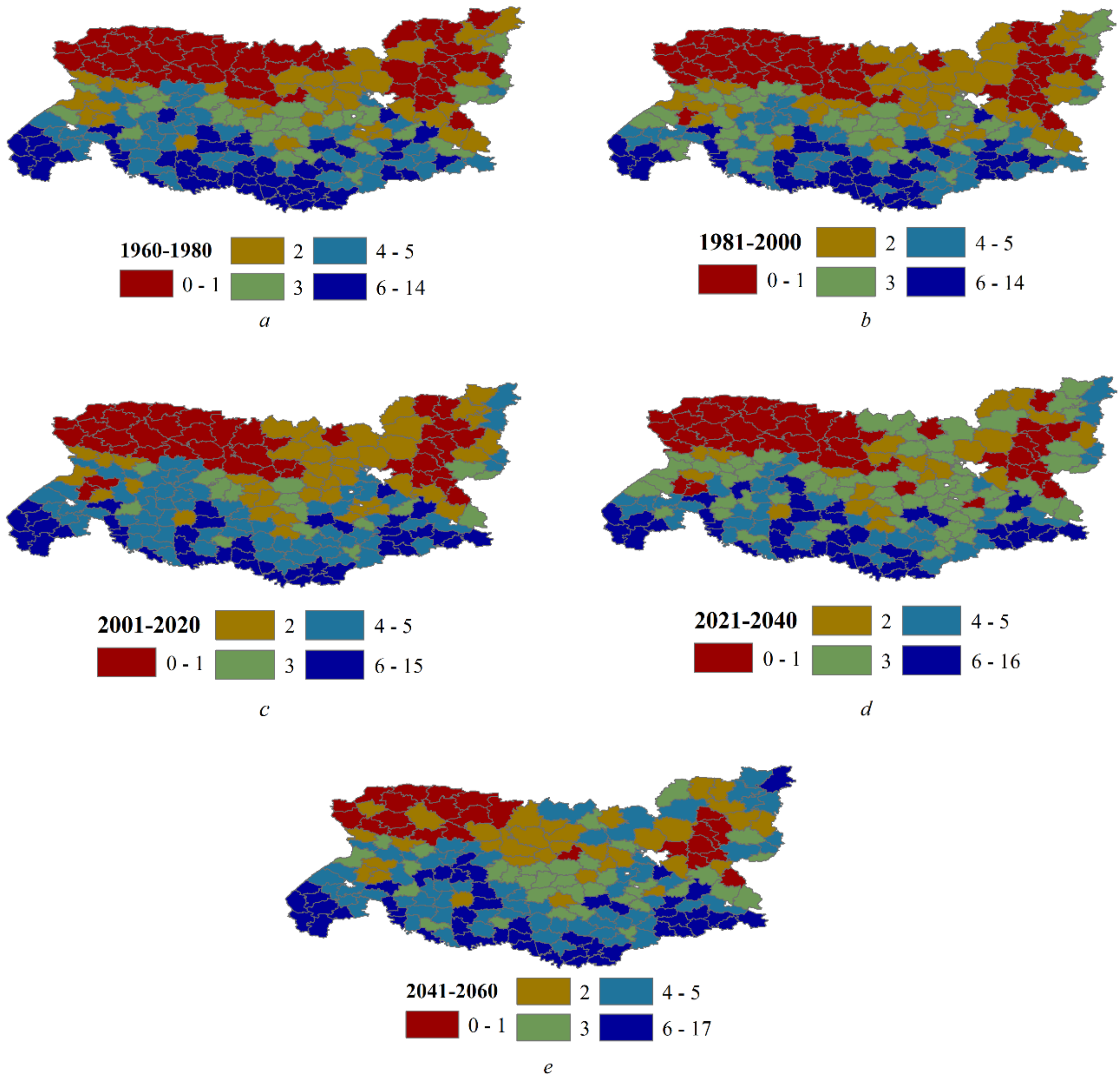

Fig. 2. Spatial variability of the intensity of soil water erosion (t/(ha*yr))

National and regional assessments of soil erosion intensity can serve as a basis for rationally targeting investments intended to protect soils from water erosion and prioritising actions for effective soil restoration. A soil loss map, disaggregated by land cover/use type, administrative units, climate zone, and soil loss class, facilitates the identification of 'hot spots' where efforts should be focused to prevent further soil degradation (Panagos et al., 2015). A cost-benefit analysis revealed that implementing erosion-control measures – such as terracing, stone walls, and cover crops – in high-erosion agricultural areas (A > 10 t/(ha*year)) could generate €1.35 billion in economic benefits across the EU (Kuhlman et al., 2010). About 76% of European land loses soil at the rates below 2 t/ha per year, which is considered sustainable according to the accepted soil formation rates (Verheijen et al., 2009). Erosion affects 35.5% of the studied region, posing considerable risks of soil loss. Forecasts predict a decline in areas with acceptable water erosion levels to 30.5% by 2040 and 28.2% by 2060. In the EU, 24% of land experiences soil loss rates of over 2 t/ha per year, responsible for nearly 87% of total soil loss. Furthermore, 5.2% of European land suffers severe soil loss (A > 10 t/(ha*yr)), accounting for 52% of total soil loss. To mitigate those events, protective measures such as reforestation are recommended (Panagos et al., 2015). In northern Ukraine, less than 2% of the territory faces soil loss exceeding 10 t/(ha*yr). National and regional assessments of soil erosion intensity are crucial for the understanding of the extent of soil degradation, identifying vulnerable areas, and implementing targeted soil conservation measures. Establishing a continuous, harmonized soil monitoring system is essential to ensure sustainable soil management, support policymaking, and address environmental challenges such as climate change, biodiversity loss, and food security. Proposals to establish a continuous, harmonized soil monitoring system at national and regional levels aim to provide comparable data and map the changes in soil degradation and its economic impacts, supporting decision-making and sustainable development goals (Ferreira et al., 2022). Increasing soil erosion forecasts emphasize the need for intensified efforts by the United Nations to combat this issue and to inform decision-makers about national strategies and regional soil conservation plans (Borrelli et al., 2020). A continuous, harmonized soil monitoring system is vital for safeguarding soil resources and ensuring their sustainable use. By combining advanced technology, standardized protocols, and international collaboration, such a system can provide invaluable insights for tackling soil degradation and achieving broader environmental and societal goals.

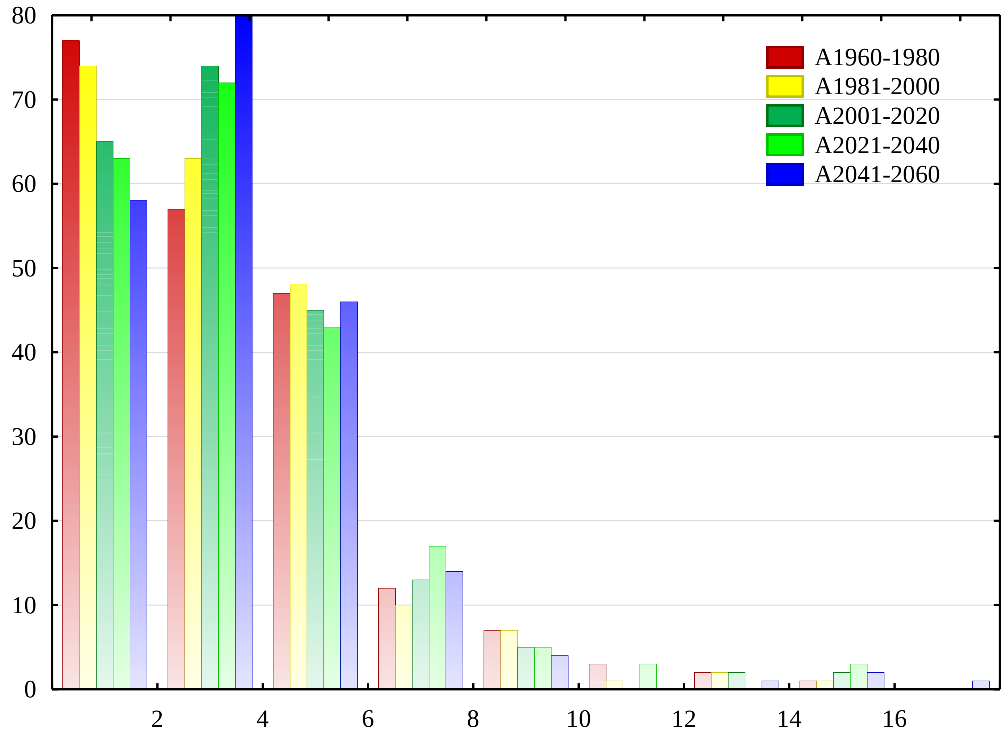

Fig. 3. Histogram of water erosion intensity distribution (t/(ha*yr))

Conclusion

Water erosion in the Ukraine's Polissia and Forest-Steppe regions is a significant environmental issue that affects soil health, agricultural productivity, and hydrological systems. Both regions have distinct environmental conditions and land-use practices that influence the prevalence and intensity of water erosion. Water erosion in Ukraine's Polissia and Forest Steppe is estimated at 2.4 to 2.6 t/(ha*yr), consistent with the European average. Only 35.5% of the area was observed to have the erosion rates below the maximum permissible level of 2 t/ha per year. The climate trends forecast a 3.0–6.5% increase in water erosion over the next decades, with a decrease in the south and an increase in other areas. Soil erosion resistance explains 26.3% of the variability in trends, precipitation accounts for 19.9%, and vegetation resistance accounts for 18.9% of climate-induced changes in erosion intensity. Water erosion remains a pressing issue in both Polissia and Forest Steppe, albeit with varying causes and impacts. Sustainable land-use practices, combined with government policies and community engagement, are essential for mitigating erosion and preserving soil health in these ecologically and agriculturally vital areas. National and regional assessments of soil erosion intensity are essential for informed decision-making. By integrating advanced modeling tools with ground observations, these assessments guide effective soil conservation strategies, mitigating the impacts of soil erosion on ecosystems, food security, and climate stability.

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