



How much cropland needs to be converted to forest to offset wind erosion risk?

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Wind erosion is one of the most underestimated forms of land degradation in European agricultural landscapes. Growing climate challenges, including more frequent and prolonged droughts as well as higher average and maximum wind speeds, significantly elevate the risk of deflation processes. However, quantitative spatial assessments of future changes in wind erosion and effective mitigation strategies remain inadequate. This study aimed to provide a detailed spatial forecast of changes in wind erosion risk due to climate change and to develop practical recommendations for optimising vegetation cover to counteract the anticipated increase in erosion potential. Modelling was conducted over a large area of Ukraine, including the Polissya, Forest-Steppe and transitional zones, using the Revised Wind Erosion Equation (RWEQ) model. The calculations incorporated detailed spatial data on climate (temperature, precipitation and wind), soil properties (grain size distribution, organic matter and calcium carbonate content) and vegetation cover and relief morphometry. Climate scenarios (SSP3-7.0, 2041–2060) were derived from WorldClim 2.1 models. Furthermore, the influence of various types of vegetation cover on reducing erosion potential was assessed. The modelling results indicate that the average annual rate of soil loss due to wind erosion is expected to increase by 1.9 times during the forecast period, while maximum values may rise by more than threefold compared to the historical period. A mosaic spatial pattern of erosion risk is emerging, characterised by pronounced risk in the northern, north-eastern and certain central regions. This risk is primarily determined by a combination of high wind speeds in winter and spring, prolonged moisture deficits (as indicated by a decrease in the potential evapotranspiration index) and low levels of calcium carbonate (CaCO₃) and organic matter in the soil, which diminish aggregate stability. In the southern and central regions, where soils are enriched with carbonates and organic matter, relatively high resistance to erosion processes is anticipated even in the face of unfavourable climate change. Based on ΔE calculations, which predict changes in soil loss, the necessary extent of structural adjustments to the cover was determined. Converting some arable land into forest plantations has been identified as the most effective way to mitigate the risk of wind erosion. The model indicates that the proportion of forested areas must, on average, be increased by 1.7% of the total land area to offset the rising potential for erosion. In certain erosion-prone regions, this requirement may exceed 90%. Forests provide a stable anti-erosion effect through the development of root systems, the addition of organic matter and the formation of a stable soil aggregate structure. They also offer long-term protection against wind. The results obtained are significant in that they facilitate the creation of spatially detailed risk maps and scenarios for the structural adaptation of land use. This data can be integrated into spatial planning systems, sustainable land management programmes and climate change adaptation strategies. The study also emphasises the need to develop erosion control strategies tailored to specific sites that consider the characteristics of the climate, soil and landscape structure. Prospects for further research include improving model parameterisation to take soil organic matter dynamics into account, integrating satellite monitoring to refine the spatial distribution of risks and evaluating the synergistic effects of structural adaptations such as carbon sequestration, increased biodiversity and stabilisation of the hydrological regime.

Keywords: wind erosion; soil degradation; climate change; land cover adaptation; forest plantations; soil conservation; environmental security; agroecosystems; spatial modelling; sustainable land management.

Introduction

The phenomenon of wind erosion of agricultural land is an environmental issue of increasing relevance in Europe (Quinton & Fiener, 2023), yet it remains underestimated. It is anticipated that climate change, particularly the increasing frequency and severity of droughts, will serve to exacerbate the risks associated with this phenomenon. Wind erosion is a key factor in the degradation of soil and the loss of essential ecosystem functions (Yakovenko & Zhukov, 2025). Moreover, this type of soil degradation gives rise to a series of off-site effects, including air pollution, adverse impacts on human health, and disruptions to natural ecosystems (Stefanovska et al., 2025). Despite its significance, wind erosion remains an area of insufficient study and poor integration into land protection policies in Europe, despite the considerable potential implications for both global and regional sustainable development challenges (Nykytiuk et al., 2024). It is imperative that a thorough comprehension of wind erosion risks and their ramifications is attained in order to formulate efficacious soil conservation strategies in the context of climate change (Bartkowski et al., 2023). In Europe, the mean annual soil loss due to

wind erosion is estimated at approximately 3.6 tons per hectare per year, with marked spatial variability. The highest rates of erosion are observed in Southeastern Europe, as well as in specific areas of Central and Western Europe, where the intensity of erosion can exceed 5 tons per hectare per year. It is estimated that approximately 17% of agricultural land is susceptible to moderate to high levels of wind erosion (Borrelli et al., 2017).

Global warming exacerbates soil moisture deficits, increases the frequency and duration of agricultural droughts, and degrades soil water regimes (Zhukov & Kunakh, 2025). These changes lead to a breakdown of soil structure, a decline in fertility, and heightened vulnerability to erosion processes, particularly wind erosion (Samaniego et al., 2018). Wind erosion is the result of a combination of natural and anthropogenic factors that reduce soil resistance to deflation and increase erosive potential. A primary cause of this phenomenon is the inadequate or seasonal variation in vegetation cover, which is incapable of providing sufficient protection to the surface from wind stress. Prolonged dry periods have been shown to contribute to the desiccation of the soil surface, the degradation of soil structure, and the weakening of particle cohesion (Jones et al., 2021). This creates fa-

avourable conditions for particle detachment and transport. The role of wind speed is particularly pronounced in open, flat landscapes where there is an absence of both natural and artificial windbreaks. Intensive farming practices involving deep tillage, in conjunction with the cultivation of crops that provide minimal surface cover, result in the disintegration of soil aggregates. The presence of a low organic matter content has been demonstrated to have a further detrimental effect on the formation of stable aggregates, thereby weakening the soil's structural resilience to wind forces. The combined effect of these factors is to establish a complex and spatially heterogeneous regime of wind erosion, the intensity of which is likely to increase in response to ongoing climate change (Lee & Gill, 2015).

The fundamental principles of wind erosion of soils are predicated on a comprehensive understanding of the interactions between wind force, soil properties, and surface conditions. When wind speeds exceed a certain critical velocity, it becomes capable of overcoming the cohesive forces binding soil particles together, resulting in their displacement. The process operates through three main transport mechanisms: saltation, defined as the hopping of larger particles along the surface; suspension, defined as the lifting of fine particles into the air and their transport over long distances; and surface creep, defined as the rolling or sliding of larger particles along the ground (Vogel et al., 2019). The capacity of soil to resist the process of erosion is contingent upon a number of factors, including but not limited to aggregate structure, the content of organic matter, the availability of calcium, moisture levels, vegetation cover density, and microrelief. Vegetation has been shown to act as a natural windbreak, thereby reducing wind velocity near the surface and helping to retain soil particles (Scheplanski, 2018). Agricultural practices that disrupt surface integrity have been demonstrated to promote soil disaggregation and increase erosion risk. Contemporary approaches to assessing wind erosion take into account not only physical factors, but also socio-economic, political, and management factors that shape the vulnerability of agroecosystems (Rosa-Schleich et al., 2019).

The study of wind erosion is an active area of research in landscapes that combine a high degree of openness, insufficient or seasonally unstable vegetation cover, and climatic conditions conducive to deflation processes. Such landscapes primarily include arid and semi-arid zones, characterised by features such as steppes, semi-deserts and deserts, in addition to agricultural plains exhibiting a high proportion of croplands, particularly those exhibiting a simplified vegetation structure. Furthermore, the term encompasses natural and anthropogenically altered landscapes exhibiting low soil resistance to degradation (Ginoux et al., 2012). In the European context, particular attention is given to regions such as the Mediterranean Basin, Central and Eastern Europe, southern Scandinavia, and lowland areas of Western Europe, where intensive agricultural use increases the vulnerability of landscapes to wind erosion. In the context of climate change, there is growing interest in landscapes with transitional moisture regimes, where increasing droughts and soil moisture deficits may significantly alter the spatial patterns of wind erosion (Webb & Pierre, 2018).

A review of recent studies indicates that wind erosion is a complex and spatially heterogeneous process whose intensity is substantially amplified under changing climatic conditions. Despite the growing pertinence of this issue for European agricultural landscapes, the quantitative assessment of expected changes in erosion risk and the development of practical mitigation strategies remain insufficiently addressed. The purpose of this study is twofold. Firstly, the aim is to undertake quantitative modelling to project changes in soil loss due to wind erosion, influenced by climate factors. Secondly, to utilise this analysis to determine the areas most at risk. Thirdly, to assess the potential of adjusting vegetation cover, particularly by increasing forest ecosystems, in order to offset the predicted increase in potential erosion.

Materials and methods

The study area encompasses a large portion of Ukraine, characterized by pronounced spatial heterogeneity of natural conditions,

covering various physiogeographical zones, including northern parts of Polissya, central and southern parts of the forest-steppe zone, as well as transitional areas (Nykytiuk et al., 2025). The relief of the territory is predominantly represented by gently undulating plains with absolute elevations ranging from 150 to 300 m, which contribute to the heterogeneity of wind flows and deflation processes. The region's climate is moderately continental, with an average annual air temperature of approximately +8 to +9 °C and an average annual precipitation ranging from 500 to 600 mm (Tkachuk et al., 2024). A clear gradient in precipitation distribution is observed: in the south-eastern part of the region, there is a tendency toward decreasing precipitation, while in the northern and northwestern areas, an increase is noted.

The soil cover is characterized by complex spatial heterogeneity. In the southern and central parts of the region, soils with elevated calcium carbonate (CaCO₃) and organic carbon content predominate, which promotes the formation of water-stable aggregate structures and enhances resistance to wind erosion. In contrast, the northern and northeastern parts of the region are dominated by acidic sod-podzolic and eroded soils with low carbonate content and weak structural stability, making them more vulnerable to deflation processes. The spatial distribution of soil organic matter exhibits marked heterogeneity: in the southern and central areas, weakly humified arable soils prevail, whereas in the northeastern part, patches of soils with higher organic matter content remain, associated with peatlands and natural meadows.

A substantial portion of the territory is used for intensive agriculture, with croplands predominating, many of which are highly susceptible to deflation. The spatial mosaic of climatic, soil, and anthropogenic factors creates a complex pattern of potential wind erosion risk, which was duly considered in the construction of the erosion risk projection model.

The Revised Wind Erosion Equation (RWEQ) incorporates the weather factor (WF), soil crust factor (SCF), soil erodibility factor (EF), surface roughness factor (K), and the cover factor for vegetation and crop residues on the soil surface (COG), as well as a field parameter to account for field size and orientation, and wind velocity adjusted for slope and hill height (Youssef et al., 2012). This model is based on field and laboratory studies (Saleh & Fryrear, 1999). As in most wind erosion models, wind acts as the primary driving force in RWEQ. The model estimates the mass of eroded particle transport ($Q(Z)$, kg m⁻¹) over specific time periods based on individual events, up to a height of 2 meters over the windward distance (Z , in meters), for a given field length. The calculation is based on the balance between wind erosivity and soil erodibility (Saleh & Fryrear, 1999; Youssef et al., 2012):

$$Q(Z) = Q_{max} \left(1 - e^{-\left(\frac{Z}{s}\right)^2} \right),$$

where Q_{max} (kg/m) is the maximum transport capacity (mass of eroded particle transport), and s (m) is the critical field length at which 63% of the maximum transport capacity is reached. These two parameters are calculated as follows:

$$Q_{max} = 109 (WF \cdot EF \cdot SCF \cdot K \cdot COG),$$

$$s = 150.71 (WF \cdot EF \cdot SCF \cdot K \cdot COG)^{0.3711},$$

where the weather factor WF (kg/m) is based on input weather parameters such as wind, snow, and soil moisture, and is calculated as:

$$WF = Wf(\rho/g) \cdot (SW) \cdot SD$$

where Wf is the wind factor (m³/s³), ρ is the air density (kg/m³), g is gravitational acceleration (m/s), SW is the soil moisture factor, and SD is the snow cover factor, calculated as 1 minus the probability that snow depth exceeds 25.4 mm.

Air density (ρ) is computed as follows (Li et al., 2020):

$$\rho = 348.0 \left(\frac{1.013 - 0.1183EL + 0.0048EL^2}{T} \right),$$

where EL is elevation (km), derived from the digital elevation model (DEM), and T is absolute temperature.

Wf and SW are calculated as:

$$Wf = \frac{W}{N} Nd,$$

where W is the wind value (m³/m³), N is the number of wind speed records used over the period (minimum 500), and Nd is the number

of days in the modelling period (e.g., 15 days over 1.5 months). W is computed as:

$$W = \sum_{i=1}^{i=n} U_2(U_2 - U_t)^2,$$

where U_2 is wind speed at 2 m height (m/s), and U_t is the threshold wind speed at 2 m height, set at 5 m/s.

$$SW = \frac{ETp - (R + I) \frac{R_d}{N_d}}{ETp},$$

where ETp is potential relative evapotranspiration (mm/day), R is rainfall (mm), I is total irrigation (mm), and R_d is the number of rainy and/or irrigated days during the modelling period.

ETp is calculated as:

$$ETp = 0.0162 \left(\frac{SR}{58.5} \right) (DT + 17.8),$$

where SR is total solar radiation (J/m^2 day), and DT is mean temperature ($^{\circ}C$).

The erodible fraction (EF) and soil crust factor (SCF) are calculated as follows (Zerihun et al., 2018):

$$EF = \frac{29.08 + 0.31Sa + 0.17Si + 0.33 \frac{Sa}{Cl} - 2.59OM - 0.95CaCO_3}{100},$$

$$SCF = \frac{1}{1 + 0.0066Cl^2 + 0.21SOM^2},$$

where Sa is sand content (%), Si is silt content (%), Sa / Cl is the sand-to-clay ratio, SOM is soil organic matter content (%), and $CaCO_3$ is calcium carbonate content (%).

Surface roughness has been identified as a significant factor influencing wind dynamics (Mandakh et al., 2016). The roughness coefficient is defined as 0 for surfaces that are characterised by extreme roughness and 1.0 for surfaces that are deemed to be flat (Saleh & Fryrear, 1999). Surface roughness is generally defined as the height at which the mean wind speed approaches zero. The roughness value is contingent on a number of factors, including but not limited to landscape undulation, the presence and density of soil clods, and vegetation height (Zingg & Woodruff, 1952). The correlation between surface roughness and wind erosion of soil is negative; that is to say, an increase in surface roughness has a suppressive effect on the transport of sand and dust. While this factor is imperative for wind erosion assessment, evaluating the spatial distribution of surface roughness across a site and the surrounding landscape is challenging and time-consuming. In this study, we utilised available remote sensing data to derive terrain characteristics. The Wind Erosion Equation (WEQ) defines roughness as a factor that limits the erosive effect of wind. In this study, the Terrain Ruggedness Index (TRI) is considered a potential proxy for regional assessment of this factor (Riley et al., 1999).

The vegetation cover factor (COG) describes the influence of crops, plant orientation, and plant residues on wind erosion and is calculated as:

$$COG = e^{-0.0438FVC},$$

where FVC is the fractional vegetation cover (%).

FVC , with a spatial resolution of 0.25 km and a temporal resolution of one month, was computed using a pixel-based model (Ivits et al., 2013) as follows:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}},$$

where FVC is the fractional vegetation cover (%); $NDVI$ is the weighted mean $NDVI$ value across vegetated and non-vegetated areas; $NDVI_{soil}$ is the $NDVI$ of bare soil pixels; and $NDVI_{veg}$ is the $NDVI$ of full vegetation cover.

The mean soil loss (SL , kg/m^2) at a given point from the upwind field boundary (Z , m) is calculated as:

$$SL = \frac{2Z}{S^2} Q_{max} \exp\left(-\frac{Z}{S}\right)^2.$$

Estimates of the length of unprotected surface in the direction of the prevailing wind (Z) were derived for each land cover type from the ESA WorldCover dataset (Zhang et al., 2021). Each land cover type was assigned an expert-estimated value representing the average length of unprotected surface (in meters), reflecting its ability to intercept or attenuate wind flow. The assigned values were as follows: forests – 20 m, shrubs – 50 m, grasslands – 200 m, cropland – 600 m, built-up areas – 10 m, bare land – 800 m, wetlands – 40 m, moss

cover – 300 m. These coefficients were applied to the respective land cover layers to generate a spatial map of unprotected surface length, which served as a basis for further wind erosion soil loss modelling. ESA WorldCover layers represent the proportion of each pixel occupied by a given land cover type; therefore, a weighted average unprotected surface length was calculated for each pixel. Each land cover type was assigned an expert-defined coefficient reflecting its wind protection potential. This approach is suitable for assessing the spatial patterns of erosion vulnerability at the geographical zone scale.

In this study, climatic conditions for wind erosion modelling were assessed based on global climate layers from WorldClim version 2.1, which include: mean monthly air temperature ($tavg$) at a spatial resolution of 10 arc-minutes (~340 m), converted to degrees Celsius by dividing by 10; total monthly precipitation ($prec$) at the same resolution; and mean annual wind speed ($wind$) at a resolution of 2.5 arc-minutes (~4.5 km). The data were downloaded using the `worldclim_global()` function from the R `geodata` package, cropped to the boundaries of the study region (`crop()`), masked to the region (`mask()`), and resampled as needed to achieve consistent spatial resolution (`resample()`). These climate variables were used to calculate the Climatic Factor (C), an indicator of wind erosion potential; potential evapotranspiration (PE) through the Thornthwaite index (Thornthwaite, 1948); as well as wind, soil moisture, and snow cover factors within the RWEQ model. This approach ensures spatial consistency of climatic parameters with other layers (soil, land cover, terrain) used in the assessment of erosion risk.

Results

Mean monthly air temperature exhibits a clear seasonal pattern, with higher values during the summer months and lower values in winter. According to the projection for 2041–2060, temperatures are expected to increase in all months compared to historical values (Fig. 1). The seasonal dynamics of precipitation remain consistent; however, a moderate increase in precipitation is projected for most months of the year, with the most pronounced changes occurring during the warmer period. The dynamics of mean monthly wind speed also show a distinct seasonal pattern, with higher values observed during the colder months. The forecast indicates an increase in mean wind speed across all months compared to the historical period, with the strongest intensification projected for the winter and early spring months. These changes in climatic variables suggest a likely intensification of warming processes, an increase in water input, and elevated wind erosion risks in the study region.

The spatial distribution of the Thornthwaite index (PE) within the study area shows a distinct gradient variability, reflecting differences in the relationship between temperature regime and precipitation (Fig. 2). PE values range from 67.9 to 239.3, with a median of 89.5 and an average value of 92.8. The lowest values (< 85), indicating a relative moisture deficit, are observed mainly in the west and southwest of the region. At the same time, the highest index values (> 100), indicating favourable moisture conditions, are recorded in the northeast of the study area. Most of the territory covers an area with moderate moisture levels (85–95), corresponding to transitional conditions between insufficient and excessive moisture supply. This spatial structure is important for interpreting spatial patterns of wind erosion, since the PE index is used as a component for calculating the climate factor (C), which directly influences the intensity of erosion processes. The spatial heterogeneity of the index also indicates the presence of zonal climatic influences, which should be taken into account in regional soil protection planning. The temporal dynamics of the PE index over the historical period and the forecast for 2041–2060 (Fig. 2b) show seasonal fluctuations, with maximum values in the summer months and minimum values in the winter period. In the forecast scenario, a moderate increase in the PE index is observed throughout most of the year compared to historical values, indicating a trend towards increased climatic moisture in the region under expected climate change conditions.

The spatial distribution of the climatic factor (C), which determines the potential of climatic conditions to cause wind erosion, shows a

clearly expressed zonal heterogeneity (Fig. 3). The values of the indicator vary from 0.096 to 2.189, with a median value of 1.108 and an average value of 1.107. The highest values (above 1.4), corresponding to areas with high erosion potential, are concentrated in the south-eastern, southern and partly central-eastern parts of the region. These

areas combine high average annual wind speeds with relatively low precipitation-evaporation ratios (PE), creating favourable conditions for deflation processes. In contrast, the western, southwestern and partly northern parts of the region are characterised by C values below 0.9, indicating a lower level of climatic pressure on the soil cover.

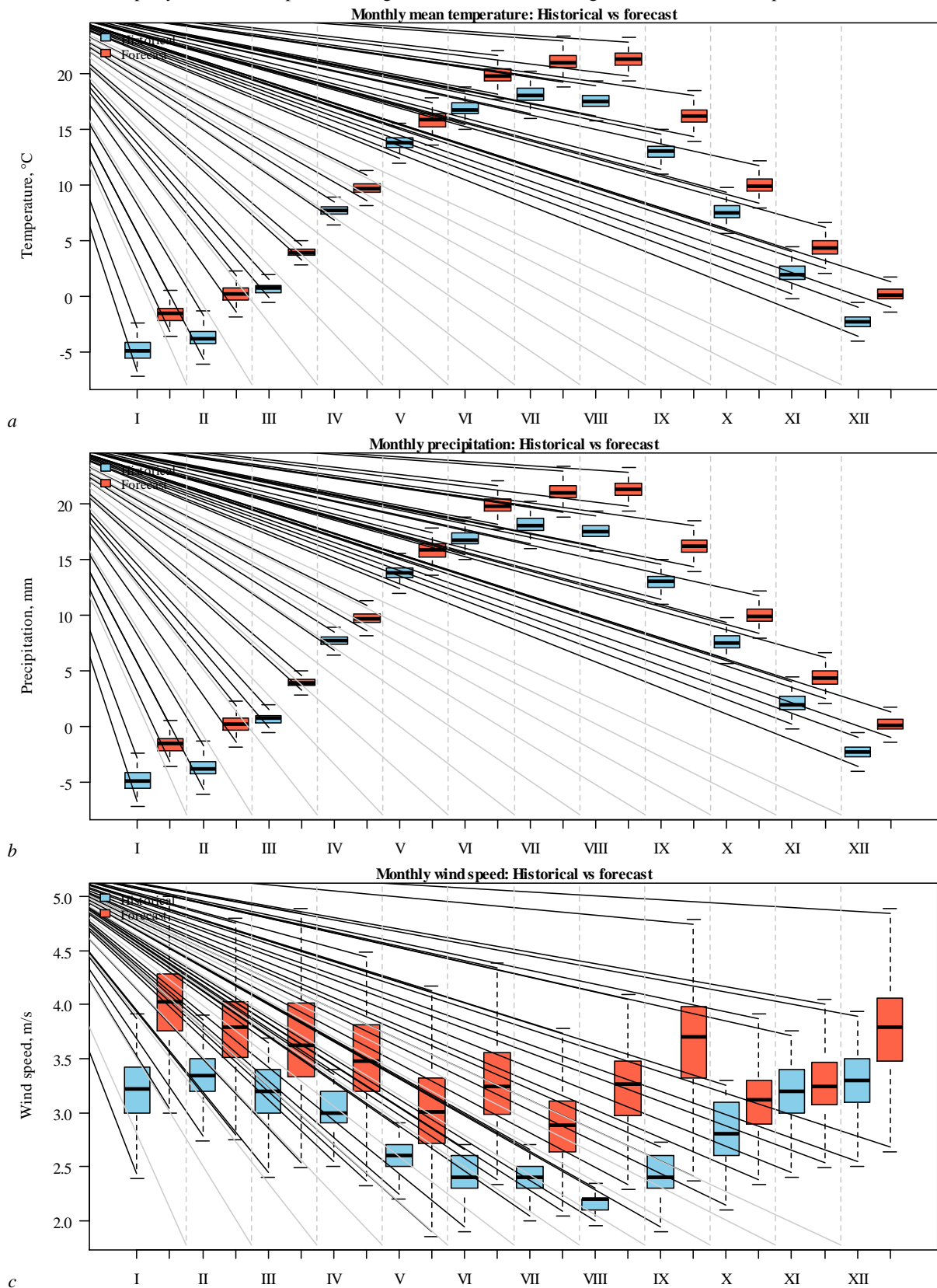
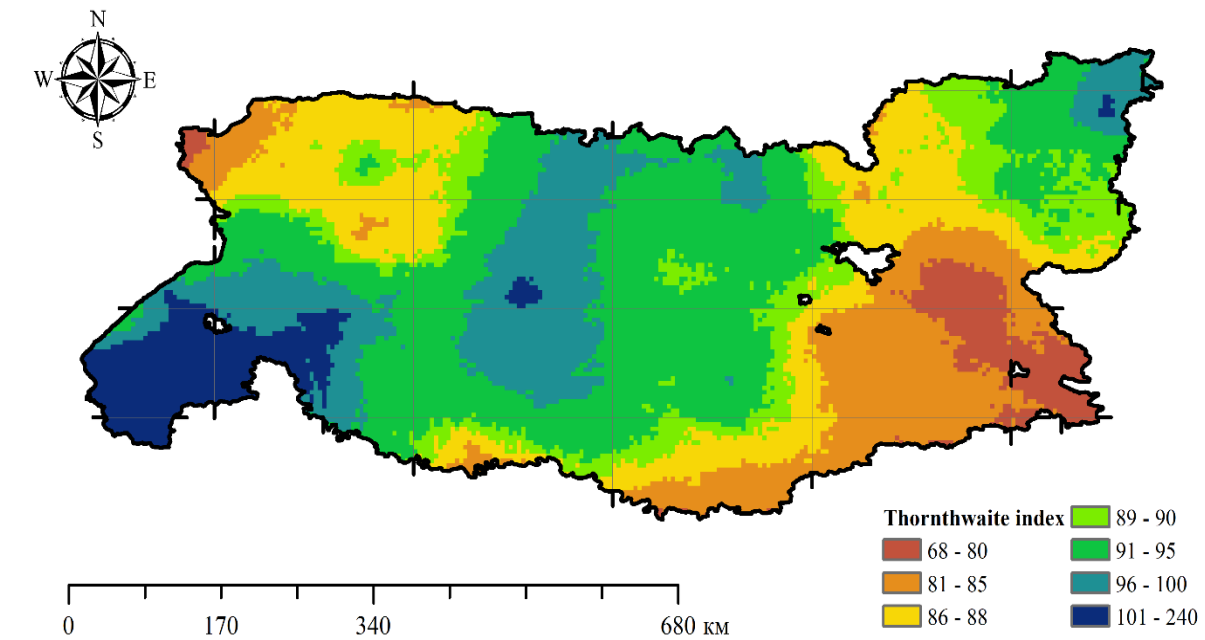
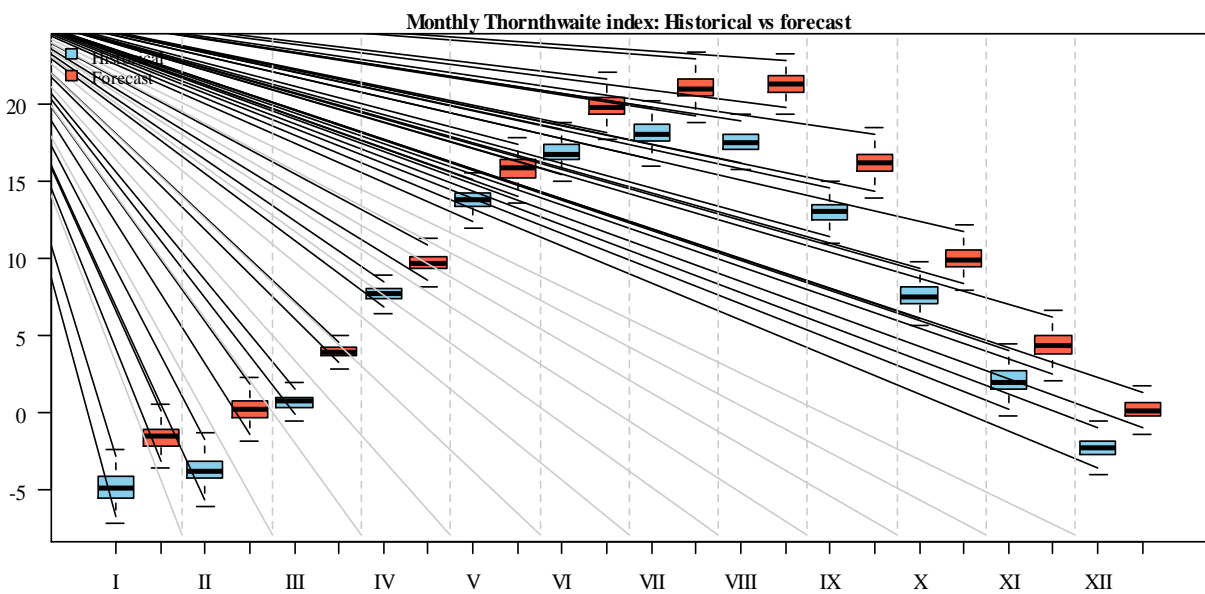


Fig. 1. Changes in climatic parameters in the modelling region for the historical period and for the climate projection for 2041–2060 (scenario SSP3-7.0, model CNRM-CM6-1): *a* – the graphs show mean monthly values of air temperature (°C), *b* – mean monthly precipitation (mm), and *c* – mean monthly wind speed (m/s); the x-axis indicates the months of the year (I–XII); the y-axis represents, respectively, temperature (°C), precipitation (mm), and wind speed (m/s); historical values (historical) and projected values (forecast) are compared



a



b

Fig. 2. Spatial distribution of the Thornthwaite index (PE) in the study area (a) and its seasonal dynamics over the historical period and according to the climate forecast for 2041–2060 (b): the index values take into account the ratio of temperature and precipitation and characterise climatic moisture: lower values (68–85) correspond to moderate or insufficient moisture conditions, while higher values (above 100) indicate areas with more favourable moisture conditions; the forecast predicts a general increase in the index throughout the year, indicating a trend towards increased climatic moisture

This is due to a combination of lower wind activity and more balanced moisture conditions. There is a regular spatial gradient structure of the climatic factor, which corresponds to geographical differences in thermal regime, precipitation and wind load, and is key to predicting areas with a high risk of wind erosion. According to the forecast for 2041–2060 (Fig. 3b), a significant increase in climate factor C is expected over most of the territory, indicating an increase in the climatic potential for wind erosion in the future. A particularly pronounced increase in C values is observed in the central and southern regions, where new areas with high erosion risk are forming. At the same time, the total area with low C values (less than 3) is decreasing, while the area with high values (more than 5) is increasing. This predicted trend reflects the combined effect of the expected increase in wind activity and changes in the water regime, which will require adaptive planning of measures to minimise the effects of wind erosion in vulnerable areas.

The spatial distribution of the soil erosion index (EF) demonstrates a pronounced mosaic structure with noticeable regional differences in the potential sensitivity of soils to wind erosion. EF values range from 0.000 to 0.325, with a median of 0.205 and a mean value of 0.189 (Fig. 3). The lowest values (< 0.13), indicating the lowest vulnerability, are concentrated mainly in the north-eastern and south-western parts of the region. They are characteristic of heavy, clayey soils with a high content of organic matter or carbonates. In the central part of the territory, there is increased erosion (0.25–0.33), which is associated with the predominance of light mechanical components (sand, sandy loam), low organic matter content and weak soil structural stability. The spatial contrast in EF values determines the heterogeneity in the potential erosion load and should be taken into account when developing regional measures to combat deflation. Analysis of the spatial distribution of calcium carbonate (CaCO_3) content in the region's soils showed significant spatial heterogeneity. Values range from 0% to 20%, with a median of 0.5% and an average value of 1.42%.

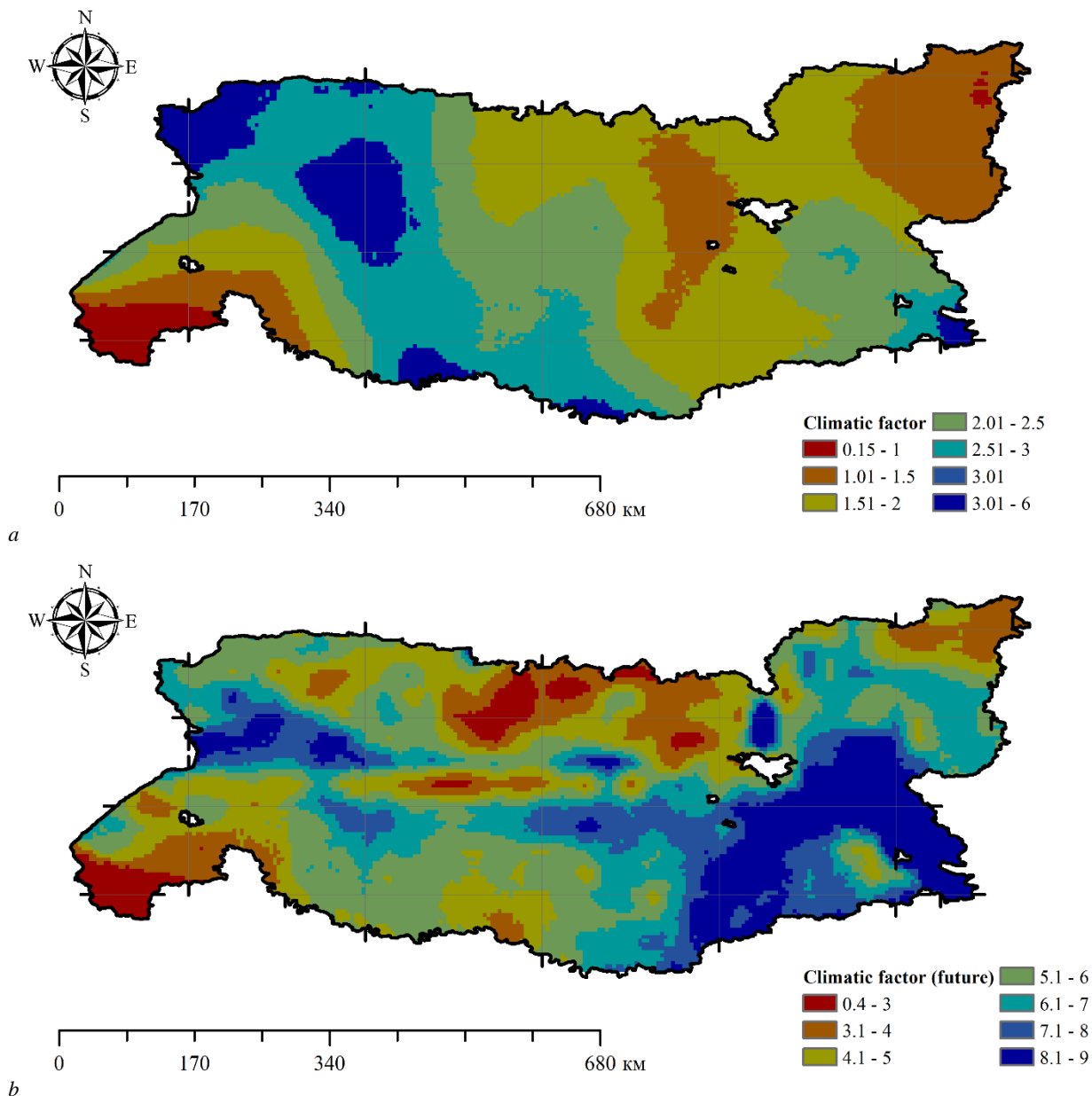


Fig. 3. Spatial distribution of the climatic factor (C) within the study area for the historical period (a) and the climate forecast for 2041–2060 (b): the value of factor C considers the combined influence of the average annual wind speed and the Thornthwaite index (PE), characterizing the potential climatic conditions for the development of wind erosion; higher values of the factor (above 1.4 in the past and above 5 in the forecast) are primarily recorded in the southern, southeastern, and central parts of the region, indicating an increased risk of erosion. Conversely, lower values (less than 0.9 in the past and less than 3 in the forecast) are predominant in the west and northwest, where conditions are less favorable for the development of wind processes; the forecast pattern indicates an overall increase in the climatic potential for erosion, which must be considered when planning soil protection measures

Most of the territory (especially the central and northern parts) is characterized by low or absent carbonate content (<0.5%), which is typical for acidic sod-podzolic and washed soils. Higher concentrations (over 5%) are recorded in the southwestern and partly northern parts of the region, where soils on limestone rocks or alluvial soils with carbonate accumulation prevail. The highest values (up to 20%) are observed in isolated areas, which may reflect areas of artificial liming or outcrops of carbonate rocks. This factor is one of the key components in the formula for calculating the erosion index (EF), since a high CaCO_3 content contributes to soil structural stability and reduces its sensitivity to wind erosion. Spatial variations in carbonate content thus significantly influence the differentiation of potential erosion risk within the study area.

The spatial analysis of soil organic matter (OM) content revealed pronounced heterogeneity within the study area. Values range from 6.5% to 22.9%, with a median of 10.3% and a mean of 11.3%. The lowest OM values (<9%) are characteristic of the southern and

central regions, where weakly humified soils and arable lands under intensive anthropogenic pressure predominate. In contrast, the highest organic matter concentrations (>18%) are observed in the northeastern and partially in the western parts of the region, indicating the presence of peatlands, humus-accumulative soil types, or preserved natural meadows. OM content is a key factor determining soil aggregate stability and water-holding capacity, and therefore significantly influences soil resistance to wind erosion. High OM values are generally associated with reduced soil erodibility, as confirmed by the analysis of the EF index. The spatial distribution of sand content (%) in regional soils exhibits a clearly defined north-south gradient. Values range from 12.3% to 77.1%, with a mean of 34.8% and a median of 29.2%. The highest values (>60%) are recorded in the northwestern and northeastern parts of the study area, corresponding to the presence of sandy and sandy loam soils, particularly alluvial, eluvial, and post-alluvial deposits. In contrast, the lowest sand concentrations (<25%) are observed in the southern and central parts of the region, where

heavy loam or clay soils predominate. Spatial patterns of sand content play a key role in shaping the erodibility index (EF), as sand is one of the main components determining the soil's susceptibility to mechanical breakdown under wind action. Regions with high sand content can be considered areas with an elevated risk of wind erosion. The spatial distribution of silt content in the soils shows a general trend of increasing proportions from north to south. Values range from 15.5% to 64.7%, with a mean of 44.1% and a median of 46.9%. The lowest values (<35%) are recorded in the northern parts, correlating with the predominance of light sandy soils. In contrast, an increased proportion

of silt (>50%) is characteristic of the southeastern, central, and southwestern areas, where loamy and structurally well-developed soils prevail. Silt is a critically important fraction for assessing erodibility, as its particles are less stable than clay but at the same time more easily picked up by the wind than sand. Spatial patterns of silt content are an important component in calculating the EF index, influencing the potential sensitivity of soils to wind erosion. Areas with higher silt content may be more vulnerable to particle loss, especially under conditions of insufficient vegetation cover.

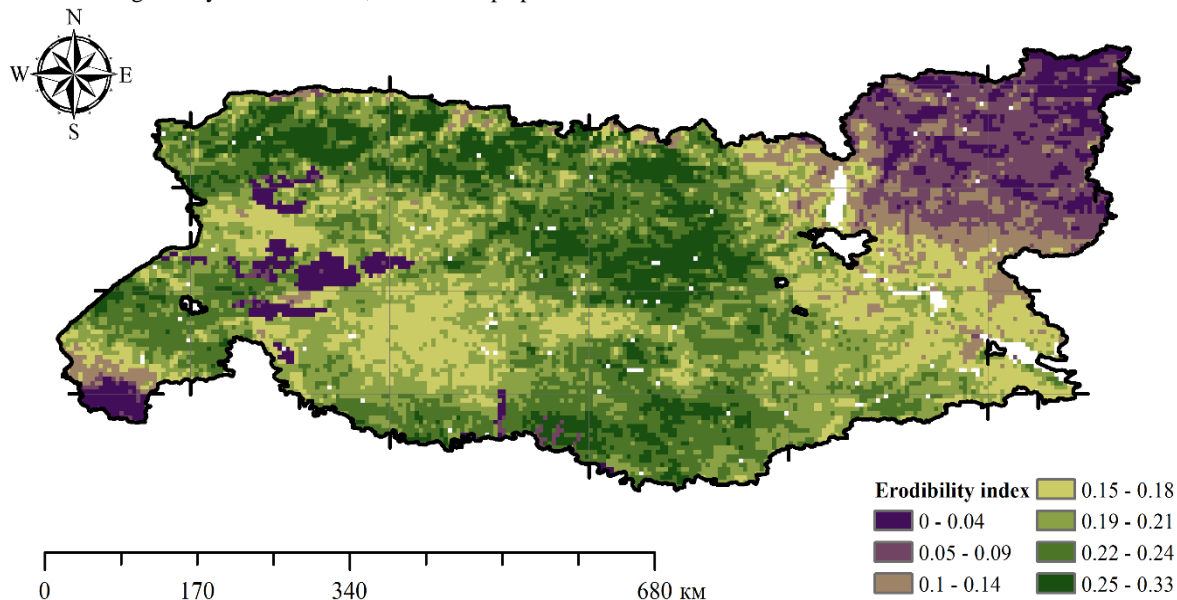


FIG. 4. Spatial distribution of the soil erodibility index (EF) within the study area: the index values indicate the potential vulnerability of the soil cover to wind erosion depending on grain size composition, organic matter content, and calcium carbonate content; the lowest values (< 0.13), which correspond to soils relatively resistant to erosion, are predominant in the northeastern and partially southwestern parts of the region; the highest erodibility values (0.25–0.33) are typical of the central and partially southern zones, where sandy or sandy loam textures combined with low organic matter content are observed

Clay content values (clay) in the 5–15 cm soil layer range from 4.8% to 39.1%, with a mean value of 22.0% and a median of 23.3%. The spatial distribution demonstrates a clear southeastward trend of increasing clay fraction. The lowest values (<10%) are observed in the northern part of the area, indicating the dominance of light sandy soils. In contrast, the highest clay concentrations (>30%) are found in the southern and southeastern regions, where heavy loam and clay soils of alluvial or loess origin prevail. Clay content significantly affects soil erosion stability. A high proportion of clay promotes particle aggregation and the formation of a structure less prone to wind-induced disintegration. Therefore, regions with higher clay content have a potentially lower risk of wind erosion. The spatial distribution of this indicator is an important determinant for calculating the erodibility index (EF) and the soil crust factor (SCF), both of which are considered in soil loss assessment.

The spatial distribution of mean annual soil loss due to wind erosion exhibits considerable spatial heterogeneity for both the historical period and the projection for 2041–2060 (Fig. 5). During the historical period (Fig. 6a), soil loss ranged from 0 to 1.054 t/ha/year, with a mean value of 0.091 t/ha/year and a median of 0.017 t/ha/year. Higher losses (> 0.25 t/ha/year) are mainly concentrated in the northern and northeastern parts of the region, where elevated climatic erosion potential coincides with less erosion-resistant soil cover types. Most of the area exhibits a moderate level of erosion (0.02–0.1 t/ha/year), while a significant portion of the southern and central zones shows very low values (<0.01 t/ha/year). According to the projection (Fig. 6b), an overall increase in erosion potential is expected: soil loss is projected to range from 0 to 3.143 t/ha/year, with a mean value of 0.170 t/ha/year and a median of 0.002 t/ha/year. The increase in both maximum values and mean soil loss indicates a trend toward intensification of wind erosion in the future. A particularly marked expansion

of areas with elevated losses (>0.25 t/ha/year) is projected for the northern, northeastern, and partially central districts. In contrast, the southern part of the region is expected to maintain relatively low erosion levels. These changes are driven by the combined effects of the anticipated increase in average wind speed and changes in climatic moisture balance (PE index), which are shaping new zones of erosion risk and require adjustments to regional wind erosion mitigation strategies.

The spatial changes in projected mean annual soil loss and the need for structural adjustment of vegetation cover to reduce erosion risk show significant territorial differentiation (Fig. 6). Changes in soil loss (ΔE) resulting from projected climate changes range from -0.336 to +2.703 t/ha/year. The median value is 0, indicating that stable or moderately positive changes prevail across most of the territory. The mean value of ΔE is +0.079 t/ha/year, and the third quartile is +0.075 t/ha/year. This indicates a moderate overall increase in erosion potential, with localized zones of significantly elevated risk ($\Delta E > 1$ t/ha/year). Based on these changes, the required increase in tree cover (% of total area) to compensate for the projected rise in soil loss was calculated (Fig. 7b). Values range from 0 to 95.5% of the pixel area. The median value is 0%, indicating that no additional increase in forest cover is needed for a substantial portion of the territory. However, vulnerable zones, predominantly in the northern, northeastern, and some central areas, require a significant increase in tree cover: the third quartile is 0.112%, and the mean is 1.72%, reflecting an uneven distribution of the need for compensatory forest planting. In the most erosion-prone areas (maximum values >20–50%), the model indicates a need to implement structural measures involving substantial changes in land cover to minimize deflation risks under projected climate conditions.

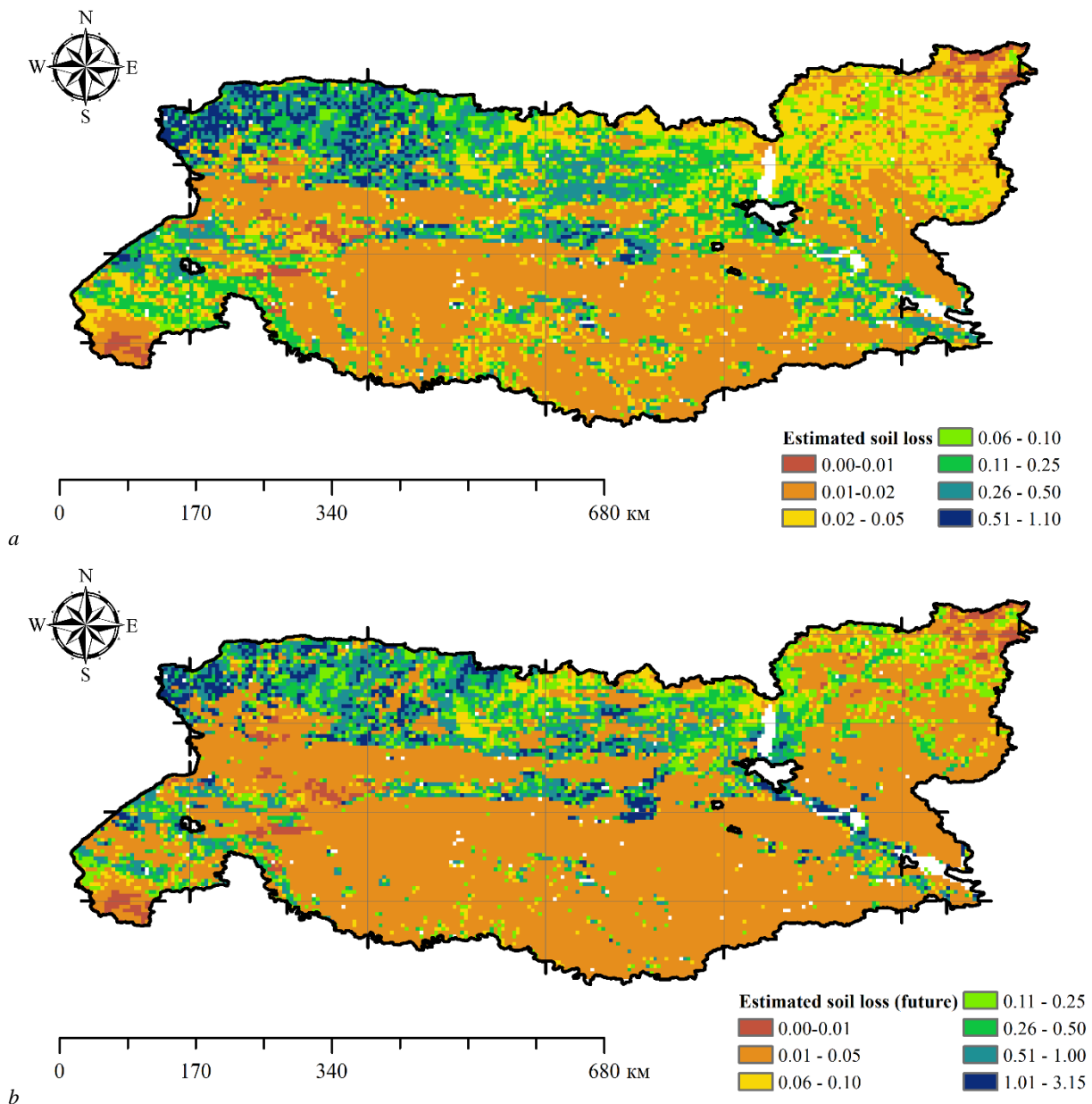


Fig. 5. Spatial distribution of mean annual soil loss due to wind erosion (estimated soil loss, t/ha/year) within the study area for the historical period (a) and according to the climate projection for 2041–2060 (b): higher soil loss values (>0.25 t/ha/year) are predominantly observed in the northern and northeastern parts of the region, where high climatic erosion potential coincides with vulnerable land use types; the projection indicates an expansion of areas with elevated soil loss, particularly in the northern part of the territory, highlighting an increasing risk of deflation processes in the future and the need to strengthen soil conservation measures

Discussion

The results of this study refine and expand conceptual approaches presented in recent review works on the issue of wind erosion in Europe (Bartkowski et al., 2023). The implementation of wind erosion risk assessment into land protection policies is particularly important against the backdrop of increasing erosion risks caused by climate change (Chetvertak et al., 2025); however, the issue of quantitative spatial forecasting remains insufficiently developed (Stefanovska et al., 2017). The results presented in this study complement these conceptual approaches by providing a quantitative assessment of the projected changes in soil loss (ΔE), identifying spatial risk patterns, and developing practical recommendations for structural adjustment of vegetation cover to compensate for the expected increase in erosion potential. The application of satellite monitoring and spatial modelling of soil erosion enables the transition from a general understanding of the problem to the development of tools for making region-specific management decisions (Wang et al., 2024). Compared to

existing quantitative estimates of soil loss from wind erosion at the European level, which are generally focused on the averaged current state of risks (Borrelli et al., 2017), the results of this study provide new information on expected changes in the spatial configuration of erosion-prone zones under the influence of climatic factors (Zelenova et al., 2024). The proposed approach makes it possible to assess the absolute values of soil loss due to wind erosion. It also defines the need for structural land-use changes at the level of individual areas, opening up new opportunities for targeted management of wind erosion risks under climate change conditions (Gruss et al., 2022). The main potential for structural adaptation of land cover is seen in the conversion of part of arable land into forest plantations, which offer significant advantages in reducing erosion risk compared to other land-use types (Kvak et al., 2018). Maintaining the existing landscape structure without considering global climate change and the increasing erosion risks would in effect mean programming a sharp decline in agricultural production and would lead to significant negative environmental consequences.

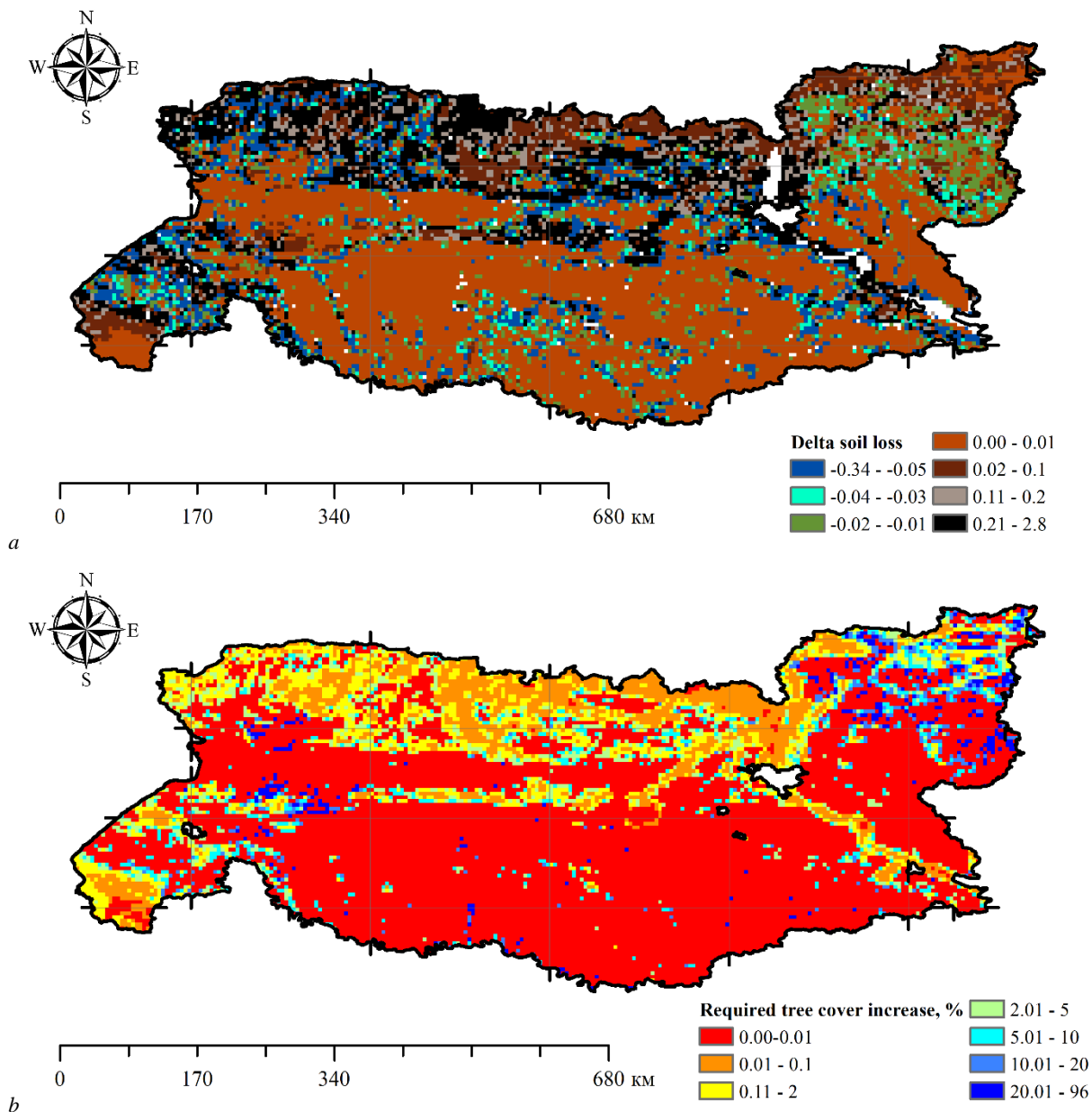


Fig. 6. Spatial changes in mean annual soil loss due to wind erosion and required adjustment of vegetation cover structure to compensate for the projected increase in erosion risk within the study area: difference (Δ) in mean annual soil loss between the projected period (2041–2060) and the historical period (t/ha/year) (a); required increase in tree cover (% of total area per pixel) calculated to compensate for the projected increase in soil loss (b); positive Δ values indicate an increase in erosion potential, which is most pronounced in the northern and northeastern areas; accordingly, in these zones, the model predicts a substantial need to increase the area of forest ecosystems (over 20% of the total area in several localized zones) to reduce wind erosion risks

Based on the obtained results, it is possible to forecast changes in the intensity of wind erosion driven by the dynamics of several key processes. An increase in both average and maximum wind speed is expected, particularly during the winter-spring period, which will enhance the erosion potential. Changes in climatic moisture (PE index) indicate a likely increase in the duration of periods with moisture deficits, which will contribute to the formation of a dry, unprotected soil surface. The modelling indicates an increase in the spatial heterogeneity of erosion processes, with the formation of localized zones of sharply increased soil loss intensity, which together result in an overall projected intensification of wind erosion in the region. The results of this study made it possible, based on projected changes in climatic indicators in the context of global warming, to assess the expected consequences of climate change for the intensity of wind erosion. The projected changes in wind erosion intensity are significant for both average and maximum values. According to the modelling results, the mean soil loss rate is projected to nearly double, and in the highest-risk zones, to increase several times. This indicates a real in-

tensification of erosion threats under the projected climate change conditions and underscores the need for adaptive changes in land-use structure. The process of increasing wind erosion risks is projected to be spatially heterogeneous. While a substantial part of the territory shows relatively stable erosion potential, significant increases in soil loss are projected in several areas (primarily in the northern, northeastern, and certain central zones). This spatial mosaic underscores the need for a regionally differentiated approach to wind erosion risk management. The resistance of soils to wind erosion in the southern and central parts of the study area is largely determined by their physico-chemical properties. In these regions, which belong to the Forest-Steppe zone, soils with elevated calcium (CaCO_3) and soil organic matter (SOM) content are widespread. A high concentration of calcium promotes the formation of a water-stable aggregate structure, while soil organic matter further stabilizes soil aggregates, enhancing their mechanical resistance to wind-induced breakdown. The combined effect of these factors reduces the deflation potential of soils in these regions. This partly explains the spatial mosaic of wind erosion

risks revealed by the modelling: even under projected increases in climatic erosion potential, soils with high CaCO₃ and SOM content demonstrate relatively high resistance to the development of erosion processes. In the context of projected climate change, it is also advisable to consider the expected dynamics of soil organic matter (SOM), which is an important factor in the structural stability of soils against wind erosion. Rising temperatures and increasing frequency of droughts may lead to a reduction in SOM content, which in turn will increase erosion risks even under unchanged climatic parameters. Therefore, maintaining an optimal level of SOM should be considered a key component of adaptive land management strategies under climate change conditions.

The high projected wind erosion risks in the northern and particularly the northeastern part of the study area are explained by a combination of unfavorable climatic trends and low soil erosion resistance. In addition to the most critical projected changes in climatic indicators in these regions (increased wind speed, reduced moisture), soil properties also play a significant role. Soils in the northern and northeastern areas contain minimal amounts of calcium, resulting in a poorly developed aggregate structure and increased susceptibility to deflation. Moreover, the organic matter in these soils is mainly represented by the surface litter layer, while the content of organic matter in the mineral part of the soil is very low. This greatly reduces the stability of soil aggregates against wind-induced breakdown, increasing erosion risk in these regions. This combination of factors creates local "hotspots" with a high projected increase in soil loss. Among all possible directions of structural land-use adaptation, the conversion of part of arable land (cropland) to forest plantations is considered the most effective alternative for reducing wind erosion risks. Forest cover provides the lowest values of the V coefficient, allowing a significant reduction in the erosion potential of the territory even with a moderate increase in its share. In addition, forests promote the formation of a stable soil aggregate structure through the development of root systems and the consistent input of organic matter, and also provide year-round soil protection, which cannot be ensured by arable crops. Considering these advantages and the additional ecosystem benefits, increasing the share of forest ecosystems is the most justified direction of structural adaptation to minimize erosion risks under projected climatic conditions. At the same time, it should be noted that the anti-erosion effect is mainly characteristic of mature or sufficiently developed forest ecosystems, which have well-developed root systems and stable understorey. In the early stages of forest restoration, the effectiveness of soil protection is limited. Therefore, achieving the desired ecological effect requires a long period of time, highlighting the need to start expanding forest cover now. Early implementation of forest expansion programs will enable the formation of the necessary protective potential of the landscape before climate changes most intensify erosion risks.

The obtained results have important practical significance for the development of adaptive land management strategies under increasing climate risks, which is a key priority in the face of these challenges. Detailed spatial maps of projected soil loss changes enable the identification of areas at high risk of wind erosion and priority zones for implementing erosion control measures (Komlyk et al., 2024). Calculating the proportion of structural adjustment required in vegetation cover provides a basis for the informed planning of measures to increase the proportion of forest ecosystems and other stabilizing forms of land use (Ponomarenko et al., 2024). This approach can be incorporated into spatial planning and decision support systems that aim to reduce erosion losses and ensure the long-term resilience of agricultural landscapes.

Future research should focus on improving the parameterisation of wind erosion models by taking local soil, geomorphological and agrotechnical conditions into account. The integration of remote sensing data and soil monitoring to refine the spatial structure of erosion vulnerability is particularly promising. Additionally, it is important to expand the analysis of land use structural transformation scenarios, assessing not only the erosion effect, but also the accompanying ecological benefits, including carbon sequestration, biodiversity enhancement and stabilisation of the hydrological regime. Furthermore, inves-

tigating the effectiveness of alternative erosion control measures under different climate scenarios would help to develop more adaptive, regionally specific strategies for ecological land use.

Conclusion

The study conducted provided new quantitative assessments and spatial patterns of wind soil erosion under current and projected climate conditions. The current state of wind erosion within the study area is characterized by significant spatial mosaic patterns: the average soil loss amounts to 0.09 t/ha/year; however, in certain zones with unfavorable soil structures and high deflation potential, significantly higher values are recorded. An analysis of the main trends in climatic factors indicates an increase in average and maximum wind speeds, a rise in the frequency of soil droughts, and a reduction in soil water reserves. Collectively, these factors create conditions conducive to the intensification of deflation processes. Model projections indicate a substantial increase in wind erosion risks in the future: average soil loss is projected to increase nearly 1.9 times, while maximum losses are expected to more than triple, resulting in the formation of "hotspots" of erosion risk in the northern and northeastern parts of the region. Expanding forested areas in place of arable land is one of the key strategies for reducing wind erosion risk under projected climate conditions. Modeling has enabled the quantitative determination of the extent of the necessary structural adjustments to land cover to compensate for the anticipated increase in erosion potential. The practical significance of the obtained results lies in the potential use of spatially detailed risk maps and structural adaptation scenarios for planning erosion control measures, integrating them into land management strategies, and making informed regional decisions. Future research prospects include improving models by incorporating soil organic matter (SOM) dynamics, conducting a more detailed analysis of alternative structural solutions under various climate scenarios, and developing adaptive agrotechnical practices and mechanisms for integrating an ecosystem-based approach to wind erosion risk management. Overall, the modeling results indicate that to effectively compensate for the projected increase in wind erosion risk within the region, it will be necessary to convert, on average, approximately 1.7% of the total area to forest, with this requirement potentially exceeding 90% of the area in certain high-risk zones. Since the formation of a stable anti-erosion effect requires considerable time, it is advisable to initiate structural adjustments to landscape cover at this stage, ahead of the projected intensification of erosion threats.

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