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Environmental and economic effects of water and deflation destruction of steppe soil in Ukraine

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Abstract: Water and wind erosion are the most powerful factors in the decrease of soil fertility and a threat to food security. The study was conducted on the steppe zone in Ukraine (total area of 167.4 thous. km^2), including agricultural land (131.6 thous. km^2). At the first stage, the modeling of spatial differentiation of water and wind erosion manifestations was carried out to calculate losses of soil (Mg·ha^{-1}) and to determine their degradation. At the second stage, soil-climatic bonitet of zonal soils (points) is carried out to determine their natural fertility (Mg·ha^{-1}). At the third stage, the spatial adjustment of the natural soil fertility to the negative effect of erosion was carried out. This made it possible to calculate crop losses and total financial losses due to water and wind erosion. The integrated spatial modeling showed that about 68.7% of arable land was constantly affected by the combined erosion, in particular the area of low eroded arable land (16.8%), and medium and highly eroded land (22.1%). Due to erodibility of soil, about 23.3% of agricultural land transferred from the category of high and medium quality to medium, low and very low quality, which is caused by the loss of soil fertility of up to 70%, crop losses of up to 1.93 Mg·ha^{-1} ha^{-1} and eduction of agricultural income up to 390 USD·ha^{-1}. In the steppe region under the research, gross crop losses from erosion were up to 15.11 thous. Mg·ha^{-1} (3.05 mln USD). In order to protect soils, improve fertility and increase crop yields in the steppe zone in Ukraine, the following measures were suggested: adaptive and landscape erosion control design with elements of conservation farming in accordance with the spatial differentiation of soil quality and extent of water erosion deflation danger.

Keywords: adaptive and landscape erosion control design, environmental and economic consequences, erodibility of soil, geomodeling, GIS-technologies, steppe zone, water erosion, wind erosion

INTRODUCTION

The expected growth of the world population in the next 30 years is the reason of the increased demand for agricultural products and the need to increase agricultural production by 60% [Levers *et al.* 2016]. In the last 10 years, the major grain exporters in the world have included the USA, Canada, Australia, Argentina, EU member states, and Ukraine. These countries together provide about 80% of the grain volume. Ukraine takes 3rd place in the world barley export (16.7%), 4th in corn export (6%), and 6th place in wheat export (5.4%) [Lisetskii *et al.* 2017]. The area of agricultural land of Ukraine is 42.7 mln ha (70.8% of the total for the country), including arable land of 32.5 mln ha (78.4% of agricultural land). The prevailing type of soil in Ukraine is chernozem, the area of which is around 17.4 mln ha (40.7% of agricultural land). The area of agricultural land per person is 0.9 ha, including arable land – 0.7 ha, which is 2.5 times higher than the average value for European countries [MENR 2012]. The plowing in Ukraine is applied to 54.6% of its territory. This has led to erosion processes in large areas and a significant violation of the ecological stability of landscapes and a significant reduction in soil fertility.

Water and wind erosion are the most powerful factors in the destruction of landscapes, the reason for the decrease of soil fertility, and a threat to food security in the country. In Ukraine, about 13.3 mln ha (31.3%) of agricultural land, including 32.6% (10.6 mln ha) of arable land, is constantly affected by water erosion [Baliuk *et al.* 2017; Petrichenko *et al.* 2013]. Land that is medium and highly eroded due to water accounts for 4.5 mln ha (13.8% of arable land), 1.5% of which has completely lost the humus horizon. 18.5% of arable land is systematically affected by wind erosion, and 61.5% is affected by dust storms [BULYGIN, ANTONYUK 2016]. Generally, the annual increase in the eroded arable land reaches 60–80 thous. ha. In general, more than 1.1 mln ha of land is degraded, low productive and technologically contaminated. More than 140 thous. ha are disturbed. About 320 thous. ha are low productive, primarily subject to conservation, restoration and improvement [BALIUK *et al.* 2017; SVETLITCHNYI 2009].

Erosion processes lead to the deterioration of physical soil properties, and the decrease and complete destruction of the humus horizon. This results in a significant decrease in humus and macro/micro elements and the deterioration of soil fertility, which decreases the value of zonal soils bonitet, decrease in crop yields of up to 60%, and the increase in the costs for agrotechnological activities [LISETSKII *et al.* 2012; PICHURA *et al.* 2017; TARARIKO *et al.* 2017]. Studies by BALIUK *et al.* [2010] found that humus removal is 310–460 kg·ha^{-1} of arable land, nitrogen – 9.0–28.0 kg·ha^{-1}, phosphorus – 21–28 kg·ha^{-1}, potassium – 180–370 kg·ha^{-1}. Over the past 100 years the humus content in chernozems has decreased from 13–14% to 3–5%.

Over the past 40 years, the irrational land use and abnormal manifestations of climatic conditions (water and wind erosion) in the steppe zone of Ukraine have led to a decrease in the content of humus by 0.36%, exchange potassium by 18%, mobile phosphorus by 34.17%, nitrification of nitrogen by 17.0% [DOMARATSKII *et al.* 2018; 2019; PICHURA 2015] in average. According to neuromodeling, it is predicted [LISETSKII *et al.* 2017] that a gradual decrease in the humus content in the soil layer may reach 0–20 cm (on non-irrigated lands by 0.01%·y^{-1} and on irrigated lands by 0.03%·y^{-1}) and the reduction of land areas characterized by medium and high humus content. The data show significant deviations as it takes 25–30 years to increase humus in soil by 0.1% in natural conditions [JENSEN *et al.* 2020; LASANTA *et al.* 2019]. A significant impact of erosion appears in all components of landscape structures, resulting in agricultural production losses that exceed 0.27–0.37 Mg·ha^{-1} of grain units [SARTORI *et al.* 2019]. Each centimeter of humus horizon lost translates into the reduced potential grain yield by 0.5–2.0 kg·ha^{-1}, and the annual environmental and economic losses due to erosion of more than USD300 per 1 ha of arable land [SARTORI *et al.* 2019].

Irrigated areas undergo irrigation erosion mainly due to the sprinkler water application. The area of irrigated land in Ukraine is 2170.5 thous. ha, of which 23.3% is irrigated area [LISETSKII, PICHURA 2016]. More than 60% of the area of irrigated land is located in the Steppe zone, excluding the temporarily occupied territories. It is about 1324.1 thous. ha, of which 461.2 thous. ha (34.8%) are irrigated. The interrupted irrigation regime leads to a rise in groundwater levels, salinization and alkalinization of soils. Preliminary studies have shown that accelerated erosion occurs in areas with an increased anthropogenic load. It leads to ecological disturbances of the natural balance in territorial ecosystems [ACHASOV *et al.* 2000; BENAUD *et al.* 2020; LI *et al.* 2020].

Therefore, it is necessary to determine the impact of water and wind erosion, frequency of its influence, their spatial distribution and the economic efficiency of agriculture, justification of environmental measures and restrictions in the use of land through the implementation of effective land management and adaptive and landscape erosion control measures combined with elements of conservation agriculture. This will strengthen the country's food security and create environmentally safe conditions for business activity and provide the framework for the sustainable land use.

MATERIALS AND METHODS

Research and assessment of ecological and economic consequences of water-deflation erosion of steppe soils in Ukraine was carried out in several stages (Fig. 1) with the use of necessary scientific methods. At the first stage, the modeling of spatial differentiation of water [CHEN *et al.* 2017; GOST 17.4.4.03-86; PHINZI, NGETAR 2019; RENARD *et al.* 1997] and wind [ACHASOV *et al.* 2000; BULYHIN 2005; MOZHEIKO *et al.* 1993] erosion was carried out to calculate losses of soil (Mg·ha^{-1}) and to determine the degree of their degradation. At the second stage, the soil-climatic bonitet of zonal soils (points) was carried out to determine their natural fertility (Mg·ha^{-1}) [KARMANOV *et al.* 1980; 2012]. The third stage involved the spatial adjustment of natural soil fertility differentiation to the impact of erosion processes. This made it possible to calculate crop losses and total financial losses due to water and wind erosion. Simulation results were used to determine the spatial differentiation of soil quality characteristics and to establish their erosion hazard in order to develop and implement adaptive-landscape anti-erosion measures with elements of soil-protective agriculture.

The study was conducted on the territory of the Ukrainian steppe zone (Dnipropetrovsk, Zaporizhzhia, Kirovohrad, Mykolaiv, Odesa, Kherson regions, total area is 167.4 thous. km^2) as shown in Figure 2, including the area of agricultural land (131.6 thous. km^2). Agricultural development of the region varies between 20 and 97%.

Methods for the first stage of research. The modeling of water erosion losses used the modified empirical and statistical model RUSLE (revised universal soil loss equation) [CHEN *et al.* 2017; GOST 17.4.4.03-86; PHINZI *et al.* 2019; RENARD *et al.* 1997]:

$$A = R \cdot K \cdot LS \cdot C{\cdot}E \tag{1}$$

where: A = average multiyear value of erosion due to runoff (rain) (Mg·ha^{-1}·y^{-1}); R = average multiyear erosive potential of rainfall (*EPR*), conditional unit; K = the coefficients of soil cover erodibility (Mg·ha^{-1}·y^{-1}); LS = terrain factor; C = erosion index of crop or crop rotation as a whole; E_{SPE} = coefficient of soil protective effectiveness of erosion control activities.

The RUSLE model is used in the environment of GIS licensed software for the ArcGIS 10.1. For this purpose, a raster model (spatial resolution 30×30 m) was created for each integrated factor of water soil erosion in the Ukrainian steppe zone. The spatial model of the average annual potential rainfall (R) was based on the extrapolation of decompositions of meteorological cartograms according to 47 meteorological stations using geostatistical method of kriging [HU, HUANG 2020] in the period of 1990–2018.

In areas where no rain intensity data are available, it is advisable to use a formula involving actual meteorological measurement data [ERDOGAN 2012]:

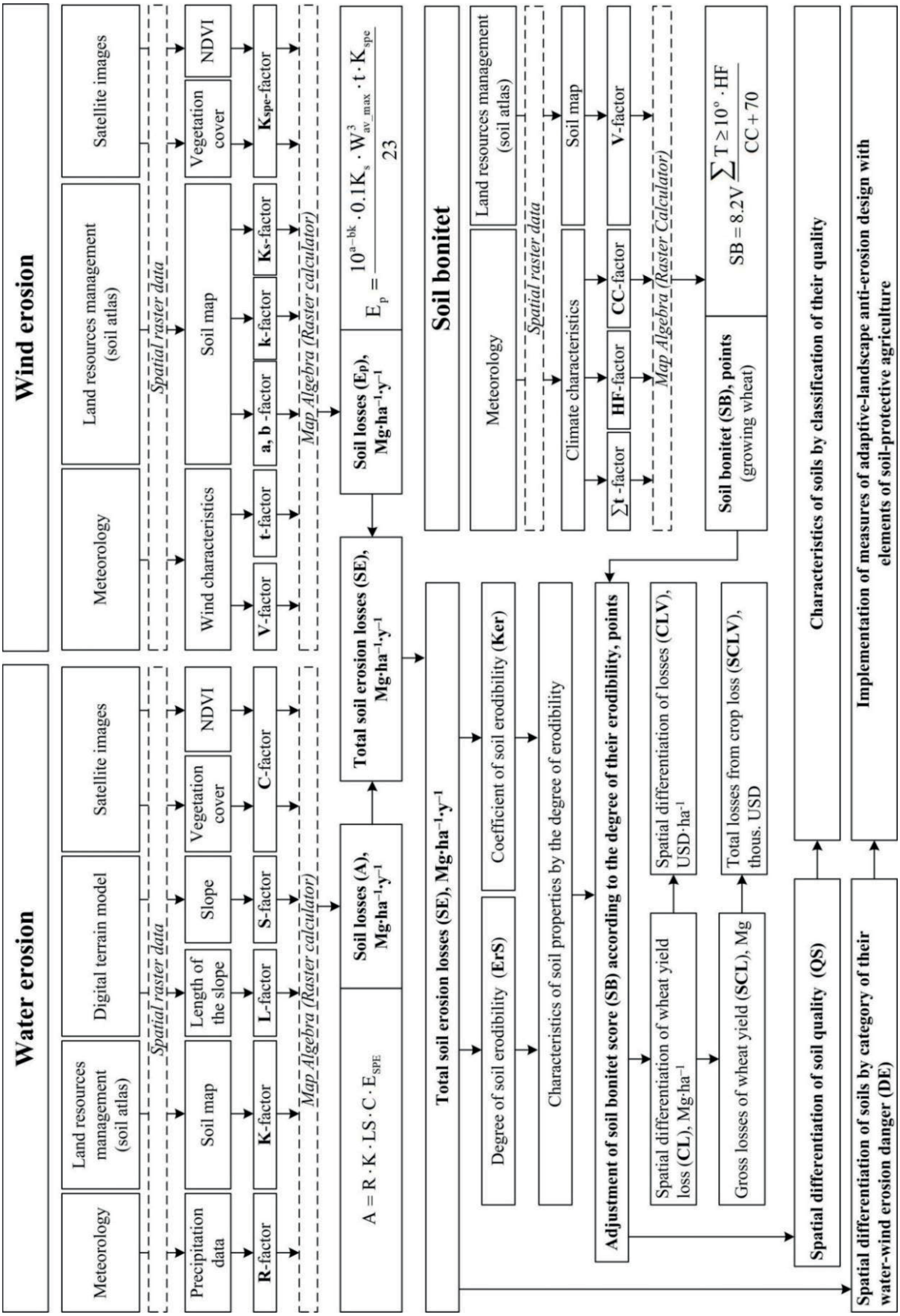

Fig. 1. Structural and logical methodological scheme of the research into ecological and economic consequences of water-deflation destruction of soils; Descriptions of symbols are presented in the text after each formula as in Equation (1); source: own elaboration

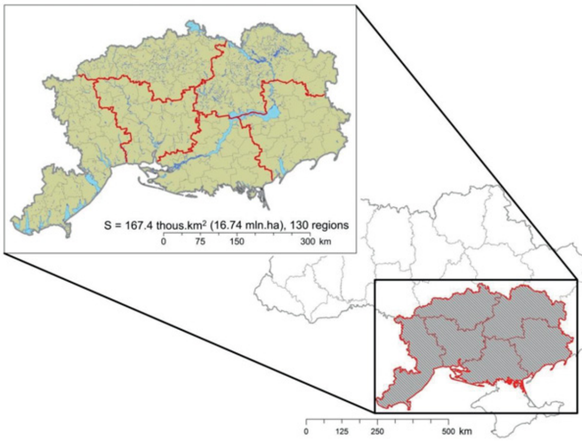

Fig. 2. Spatial characteristic of the Ukrainian steppe zone; source: own elaboration

$$R = \sum_{i=1}^{12} 1.735 \cdot 10^{\frac{1.5\log\left(p_i{}^2\right)}{P} - 0.8188} \tag{2}$$

where: p_i = monthly average precipitation (mm); P = average annual precipitation (mm).

The vectorization of soil maps covering the Ukrainian steppe (Fig. 3) was carried out while determining the factor of soil erodibility or the factor of soil compliance to erosion processes (*K*). Parameter *K* was calculated [Grushetsky *et al.* 1990] and spatial raster model was obtained for each soil type according to its granulometric composition in line with the soil erodibility coefficients (Mg·ha^{-1}·y^{-1}) – Table 1.

The erosion potential of the terrain (*LS*) was evaluated using the spatial analysis of the hydrological correct digital elevation model (*DEM*) with the spatial resolution of 30×30 m [USGS undated]. Morphometric characteristics of the relief were defined and raster cartograms of lengths (*L*) and slopes (*S*) of the surface were constructed using the "Hydrology tools of the Spatial Analyst Tools and Surface of the Spatial Analyst Tools" working module. Then the value *LS* for each pixel was calculated using the "Raster Calculator" module according to the equation [GOST 17.4.4.03-86]:

$$LS - L^{0.5}\left(0.0011S^2 + 0.0078S + 0.0111\right) \tag{3}$$

The coefficient of the vegetation cover (*C*) together with the *LS* factor are the most sensitive to the soil loss [Benkobi *et al.* 1994; Biesemans *et al.* 2000]. The soil loss is reduced with the increase in vegetation. Data from the Earth Remote Sensing (*ERS*) and correctly calibrated satellite images of Landsat-8 with geometric resolution (spatial resolution) ~30×30 m in March

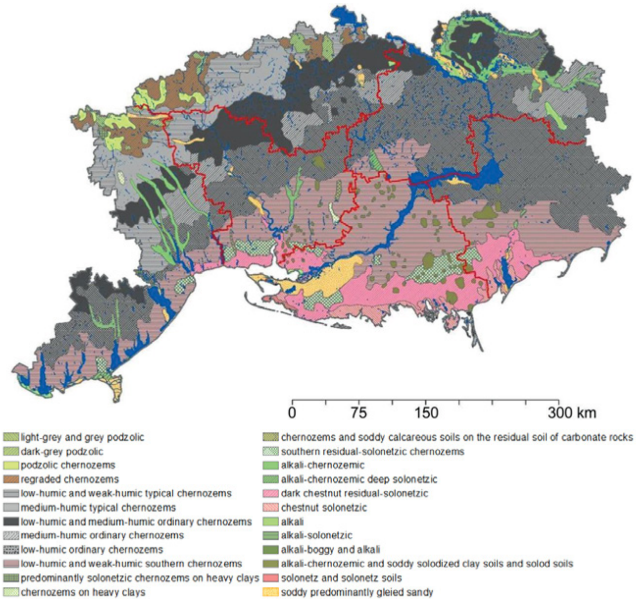

Fig. 3. Types of soils in the studied steppe regions; source: own elaboration

Table 1. Coefficient of soil cover erodibility (*K*)

The main types of soil	*K* (Mg·ha^{-1}) depend on granulometric composition of soils			
	heavy loam	medium loam	light loam	sandy loam
Sod podzolic on cover sediments	3.0	3.3	3.7	3.6
Light gray forest	2.7	3.0	3.4	3.6
Gray and dark gray forest	2.0	2.4	2.8	–
Chernozems podzolized	1.2	1.6	1.9	1.9
Chernozems typical	1.4	1.8	2.0	–
Chernozems common	1.2	1.6	1.8	1.8
Chernozems southern	1.5	1.6	2.0	–
Chernozems carbonate	1.5	–	–	–
Dark chestnut	–	2.1	–	–
Dark chestnut carbonate	2.4	2.6	–	–
Chestnut	2.5	2.6	–	2.3
Chestnut carbonate	2.6	2.8	2.3	–
Light chestnut	2.6	2.5	3.0	2.0

Source: Grushetsky *et al.* [1990].

and August 2018 were used to determine factor *C*. Generation of factor *C* values was based on the dimensionless index *NDVI* (normalized differential vegetation index). The following formula was used [Rendana *et al.* 2017]:

$$C = \exp\{-\alpha[NDVI/(\beta - NDVI)]\} \quad (4)$$

where: α and β = dimensionless parameters that determine the shape of the curve, which refers to *NDVI* and *C* factor. Parameters α and β have value 2 and 1, respectively.

The coefficient of soil protection measures (E_{SPE}) is equal to one, because additional anti-erosion measures throughout the study area are virtually absent.

To determine the potential soil loss in the Ukrainian steppe, the model of wind erosion by the National Science Center "O.N. Sokolovsky Institute for Soil Science and Agrochemistry Research" (Ukr. Natsional'nyy naukovyy tsentr "Instytut gruntoznavstva ta ahrokhimiyi im. O.N. Sokolovs'koho") was adapted to different physical-geographical conditions in the country [Achasov *et al.* 2000; Bulyhin 2005; Mozheiko *et al.* 1993]:

$$E_p = \frac{10^{a-bk}\, 0.1 K_s\, W^3_{\text{av\_max}}\, t\, K_{spe}}{23} \quad (5)$$

where: E_p = potential deflation soil loss (Mg·ha^{-1}·y^{-1}); *a*, *b* = exponential coefficients depending on the genesis, granulometric composition, density and other soil properties (calculated experimentally); *k* = clodding of the surface (0–3 cm) soil layer (content of aggregates or particles more than 1 mm) (%); K_s = destruction coefficient for aggregates of the surface soil layer under the influence of impacts of soil particles and their abrasion by an air-dust flow; $W_{\text{av\_max}}$ = average maximum wind speed during dust storms of the 20$^{\text{th}}$ occurence (m·s^{-1}) (20% occurence shows that this indicator, which was determined according to multi-year data, is true in 80 out of 100 cases, which means that in 20% of cases only the wind speed is higher during dust storms); *t* = average number of hours with the effect of wind erosion per year according to multi-year data; K_{spe} = coefficient of soil protective effectiveness of anti-deflation activities; 23 = basic flow velocity in an aerodynamic plant, which is equal to 23 m·s^{-1} in terms of the height of the wind vane (10 m); 0.1 = recalculation from g·m^{-2} for 5 minutes to Mg·ha^{-1}·y^{-1}.

Spatial models for the distribution of the regression coefficient magnitudes (*a b*), clodding (*k*) and destruction coefficient (K_s) have been created based on the assigning of corresponding values (Tab. 2) to each soil variety of the Ukrainian steppe zone (Fig. 3). Raster models for the spatial distribution of the average maximum wind speed during dust storms ($W_{\text{av\_max}}$), the average number of hours with wind erosion per year (*t*) in the territory of steppe soils have been obtained based on the extrapolation of meteorological cartogram decomposition according to 47 meteorological stations in 1990–2018.

Table 2. Values of wind erosion calculation values for the main soils of Ukraine

Type of soils	Soils description	*a*	*b*	*k*	K_s
Sod-podzolic, sod podzolized, gleyed, podzolized sandy, clay-sandy and sandy-loam soils	These soils were formed under the conditions of excessive moisture under pine and mixed forests. Humus content in the arable layer of these soils is low and ranges from 0.7–1.0% in sandy and sandy–loam to 1.5–2.0% in loamy soils. They are tight (1.40–1.55 g·cm^{-1}), store little moisture, have high water and air permeability, low absorption capacity and lack of nutrients, the soil solution is acidic – pH 4.2–5.2.	2.3497	0.0339	15–20	0.75–0.9
Peat-bog soils and peatlands	These are soils with a large number of undecomposed and semi-decomposed plant residues (peat), which are accumulated under the impact of prolonged excessive moisture. The soils are mostly characterized by an alkaline reaction of the soil solution. Average pH values of an aqueous solution in the organogenic layer are 7.3–8.2, salt pH is from 7.0 to 7.5.	6.1675	0.0918	43–66	0.9–1.0
Gray podzolized soils, podzolized and solonetzic chernozem soils, chestnut solonetzic soils, loamy and clay solonetz	Gray podzolized soils formed under forest vegetation. They occur on watershed plateaus. They have a clear differentiation of the profile by the eluvial-illuvial type. The reaction of the soil solution is acidic, fulvic acids predominate in the humus. The soils show the depletion of nutrients, humus content is 1.5–2.7%. Podzolized and solonetzic chernozems contain 3.0–4.0% of humus in the arable layer, its amount gradually decreases with depth. The availability of mobile forms of phosphorus and potassium is mostly average; it is low in one third of the soils. The reaction of the soil solution is slightly acidic, close to neutral (pH 5.6), so the soils need liming only in some cases. The thickness of the humus layer of chestnut solonetzic soils is 25–50 cm. They have a pronounced eluvial-illuvial differentiation of the profile. Humus content is 2.0–3.0%.	3.0052	0.0252	48–52	0.3–0.7
Typical and ordinary not eroded and weakly eroded chernozems, meadow soils, meadow-chernozem soils, chernozem-meadow soils	These soils are characterized by high natural fertility with a high content of humus (4.0–5.0%), have a slightly acidic reaction of the soil solution (pH 5.7–6.4). The amount of absorbed elements ranges from 25.0 to 35.0 mg-eq. per 100 g of soil, and the degree of saturation of the elements reaches 90.1%. The humus horizon is 70 cm or more.	3.4915	0.0351	29–46	0.5–0.6
Typical and ordinary medium- and highly eroded chernozem soils	By their granulometric composition, typical chernozems are mainly light loamy, less often they are heavy loamy. They have significant reserves of humus (4.0–5.0% in low-humus to 6.0–8.0% in medium-humus soils), high	4.3060	0.0580	26–44	0.4–0.6

cont. Tab. 2

Type of soils	Soils description	*a*	*b*	*k*	K_s
	nutrient reserves. The content of mobile compounds of nutrients rarely changes depending on the level of agricultural technology, the degree of humidity, and other characteristics. The degree of mobile phosphorus supply is mainly medium, of potassium – high, medium and low, of nitrogen – medium and high. Due to relatively shallow deposits of calcium and magnesium carbonates, there is a neutral or slightly alkaline, close to neutral, reaction of the soil solution (pH of salt extract is 6.3) in the humus horizon of these soils. The hydrolytic acidity of deep chernozems is very low: on average, it is 1.3 mg-eq. in the arable layer, and 0.3–0.6 mg-eq. per 100 g of soil at a depth of 50–70 cm. The amount of absorbed elements is high – 30.1 mg-eq. per 100 g of soil in the humus horizon, the saturation with the elements is 96%.				
Southern chernozem soils of all types except solonetzic	These soils formed in the southern part of the Steppe zone. The humus horizon usually reaches 50–85 cm. Humus content in heavy-textured soils is 2.5–4.3%, in medium loamy soils, it is 2.0–3.0%.	3.6955	0.03773	31	0.6
Southern solonetzic chernozem soils	These soils develop on clays, often saline, which causes the formation of the solonetrization process. Compared to other chernozems, they contain less humus (2.0–2.5%) and have worse water-physical and physicochemical characteristics.	2.7830	0.0200	29–43	0.6–0.8
Sandy-loam and clay-sandy chernozem soils	These soils have a light loamy and sandy texture with a humus content of 0.4–2.0%. The level of saturation with the elements is 75–80%. The characteristic of the profile is the same as in other chernozems.	3.6627	0.0218	23–45	0.6–0.8
Chernozem soils on dense clays	Occurrence on dense clays leads up to unfavorable physical properties. Soil horizons are very dense, impervious, viscous when wet, difficult to cultivate, get flooded, form hard lumps after drying. These soils contain a significant amount of humus (6.3% in the arable layer), are characterized by low acidity in the humus horizon (salt pH is 6.2–6.4), a neutral reaction in the lower genetic horizons, low hydrolytic acidity and high values of absorbed elements (1.5–3.0 and 43.6–50.2 mg-eq per 100 g of soil, respectively). The saturation with the elements is close to absolute – 94.7–99.0%.	3.4915	0.0351	27–42	0.6

Explanations: *a*, *b*, *k*, K_s as in Eq. (5). Source: own elaboration.

The coefficient of soil-protective effectiveness of deflation resistance activities (K_{spe}) was calculated using the modified crop erosion index (*C*') according to the formula:

$$C = C/C_{\max} \tag{6}$$

where: *C* = vegetation cover coefficient; the *C* value is calculated according to Equation (3).

The value *C*' is within 0 (maximum anti-deflation effect of vegetation cover) and 1 (minumum or absent anti-deflation vegetation).

Methods for the second stage of research. The method of zonal soils fertility according to Karmanov *et al.* [1980; 2012] and Bulgakov *et al.* [2013] was adapted and tested in accordance with the uniform comparative scale for assessment of soil fertility to create spatial models of soil bonitet in the Ukrainian steppe. Both soil properties and climate bonitet were included in this method while considering main climatic indicators that are correlated with the yield capacity, i.e. the amount of active temperatures, moisture ratio, and continental climate. The methodology reflects the general regularities of spatial distribution of yielding capacity according to natural physical and geographical zones and allows to calculate the points of bonitet for crops according to the equation:

$$SB = 8.2V\frac{\sum T \geq 10^{\circ}\ HF}{CC + 70} \tag{7}$$

where *SB* = point of bonitet; *V* = coefficients of agro-groups according to I.I. Karmanov's method; $\Sigma T \geq 10°$ = average annual sum of active temperatures ≥10°C; *HF* = humidity factor according to M.M. Ivanov (*HF* that is more than 0.9 is taken equal to 0.9); *CC* = continentality coefficient.

Information about the terrain enables to extrapolate climatic characteristics for each local element of the landscape. This helps to specify microclimate conditions and, accordingly, to set the point of soil bonitet.

The calculation of soil and climatic potential and resulting raster models for its distribution should be implemented according to the formulas for zonal soil bonitet points in the working module of the ArcGIS Raster Calculator.

The continentality coefficient (*CC*) is calculated according to the following formula:

$$CC = \frac{360(T_{\max} - T_{\min})}{\varphi + 10} \tag{8}$$

where: T_{max} = the average monthly temperature of the warmest month; T_{min} = the average monthly temperature of the coldest month; φ = the latitude.

The humidity factor (*HF*) is calculated according to Equation (9):

$$HF = P/E \tag{9}$$

where: *P* = the average annual precipitation (mm); *E* = the average annual evaporation ($g \cdot cm^{-2}$).

The summary soil indicator for the territory of Ukraine should be determined in accordance with coefficients of agro-groups by I.I. Karmanov's method (*V*) from 0.5 to 0.98 (Tab. 3).

Table 3. Values of agro-group coefficients by I.I. Karmanov's method (*V*)

Soil	*V*
Soddy-sand and chestnut-solonetzic soils	0.50
Podzols	0.67
Sod-podzolic	0.73
Forest storms	0.81
Light gray forest	0.78
Gray forest	0.81
Dark gray forest	0.86
Chernozems:	
– podzolic	0.92
– leached	0.96
– typical	1.00
– ordinary	0.96
– southern	0.92
Meadow-chernozem:	
– forest-steppe zone	0.92
– steppe zone	0.96
Dark chestnut	0.86
Chestnuts	0.81
Light chestnut	0.78
Meadow and chestnut	0.90
Brown	0.85
Gray-brown	0.88
Gray soils	0.90
Meadow-chernozem	0.85
Sod-carbonate:	
– typical	0.92
– leached	0.90

Source: KARMANOV [1980].

Spatial models for active temperatures, humidity and continentality of the climate, which are presented and described in the Results and Discussion Section, are based on the extrapolation of decompositions of publicly available WorldClim [undated] data, additional data from individual weather stations, and the national atlas.

To specify the assessment of the spatial soil condition differentiation, the calculation of the points of bonitet included the factor of complex negative impact of water and wind erosion, which determined the degree of soil degradation and the loss of crops.

Modeling and analysis of the spatial distribution of the soil condition indicators for the Ukrainian steppe were carried out in the GIS environment licensed software of ArcGIS 10.1.

RESULTS AND DISCUSSION

As a result of geomodelling, the spatial heterogeneity of the main water erosion and soil degradation factors in the Ukrainian steppe was determined, i.e. the erosive potential of rainfall (*R*) uniformly increases from south to north-west from 5.4 to 8.8 (Fig. 4a); the potential annual loss of fertile top soil (*K*) (depending on the erosion potential of precipitation) decreases from north to south from 3.6 to 1.2 $Mg \cdot ha^{-1}$ (Fig. 4b); the erosion crop index (*C*) is within 0 and 1.4 in the direction from north to south (Fig. 4c); the importance of the terrain factor (*LS*) varies from 0.2 to 1.8 (Fig. 4d); agricultural land of northwestern area of the Ukrainian steppe has the highest erosion risk. As a result of GIS modeling using the modified RUSLE model, the erosion risk was assessed, and the potential annual soil loss of arable land was calculated (Fig. 4e). About 4304.5 thous. ha of arable land was allocated. It has increased (more than 2 $Mg \cdot ha^{-1} \cdot y^{-1}$) the erosion risk (32.7% of the total arable land). Conventionally erosion free land belongs to plains and buffer borders of watersheds and they occupy 67.3% of the total arable land. However, they are subject to water erosion [DUDIAK *et al.* 2019a].

The study determined the increase in air and soil temperature fluctuations, reduction of the amount of the annual precipitation [PICHURA *et al.* 2019], hydrothermal coefficient, and the reduction of the frost-free period. The increased activity of wind contributes to the development of deflation processes. This is determined by the influence of the climate which supports erosion due to its continentality [LISETSKII 2012].

Wind erosion is significant in arid and semiarid areas that have little rainfall, high air temperature and evaporation, further enhanced by strong winds and low differentiation of plant protection. First and foremost, wind erosion primarily occurs in the steppe, which is characterized by a light granulometric composition, low speed of soil formation, medium and low humus content, and poor connectivity and strength of a soil clod. In the steppe, which is mainly flat, wind acquires a high velocity that implies an increase in particle transfer.

Deflation impact on the soil cover is associated with wind-related factors (speed, frequency, force and duration); characteristics of the earth's surface (vegetation, height and density of cover, surface roughness, availability of soil moisture), soil specifics (size of sites, their connectivity, the distribution of units and amount of organic matter) [BULYHIN 2005; CHI *et al.* 2019; LUO *et al.* 2018]. As a result of wind erosion, 5–6 mln ha of fertile land are damaged in the open steppe every year. The most active and harmful form of wind erosion occurs in the steppe and partly forest-steppe zones when wind speeds exceed 12–15 $km \cdot h^{-1}$. The research found that low efficiency of existing contour-meliorative anti-deflation activities in the Ukrainian steppe caused a large-scale disaster of 2007, when about 20% of agricultural land was exposed to dust storms. In this regard, soil loss ranged from 10 to 400 $Mg \cdot ha^{-1}$ [CHORNYI *et al.* 2007].

The spatial modeling resulted in a raster model highlighting the spatial differentiation of wind erosion factors and calculations of deflation soil loss in an area concerned. Regression coefficients (*a, b*), clodding (*k*), coefficients of destruction (K_s) for major soils in Ukraine were calculated in accordance with the potential soil loss method [ACHASOV *et al.* 2000; BULYHIN 2005; MOZHEIKO *et al.* 1993]. The study determined that the coefficients, granulometric composition, density and other properties of soils in the region

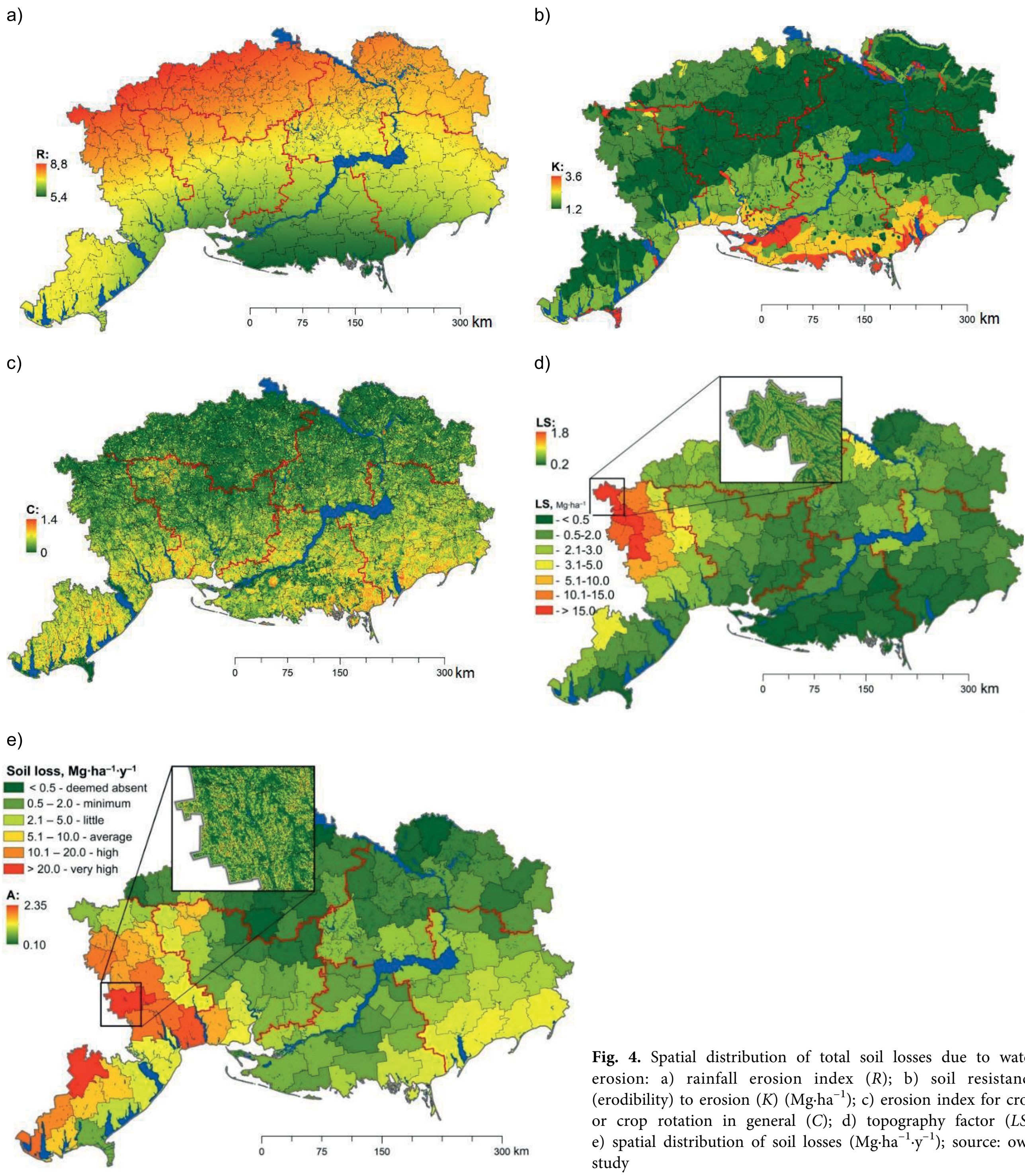

Fig. 4. Spatial distribution of total soil losses due to water erosion: a) rainfall erosion index (*R*); b) soil resistance (erodibility) to erosion (*K*) (Mg·ha^{-1}); c) erosion index for crop or crop rotation in general (*C*); d) topography factor (*LS*); e) spatial distribution of soil losses (Mg·ha^{-1}·y^{-1}); source: own study

vary by factor *a* (Fig. 5a) from 2.3497 (sod-podzolic, sod podzolized, gleyed, podzolic sandy soils, clay-sandy and loamy soil) to 4.3060 (chernozem soils typical and common medium and highly eroded soils), factor *b* (Fig. 5b) from 0.020 (chernozems southern solonetzic soils) to 0.058 (chernozem typical and common medium and highly eroded soils).

The average value of factor *k* (Fig. 5c) varies within 17.5% (sod-podzolic, sod podzolized, gleyed, podzolic sandy soils, clay-sandy and loamy soil) and 50.0% (gray podzolics, podzolic and alkaline chernozems, chestnut alkaline, alkaline loamy and clay soils), factor K_s (Fig. 5d) varies within 0.5 (chernozem soils typical and common medium and highly eroded soils) and 0.83 (sod-podzolic, sod podzolized, gleyed, podzolic sandy soils, clay-sandy and loamy soil). The average maximum wind speed during dust storms of a 20% security (W_{av_max}) decrease from the south-eastern part to the north-eastern part of the region from 26.1 to 13.7 m·s^{-1} (Fig. 5e).

The average number of hours per year with dust storms (*t*) in the steppe also varies from 0 to 37.8 h (Fig. 5f) in the same direction. Considering the spatial differentiation, the deflation impact of factor *C*' depends on the distribution of land occupied by natural vegetation and agricultural crops. The seasonal value

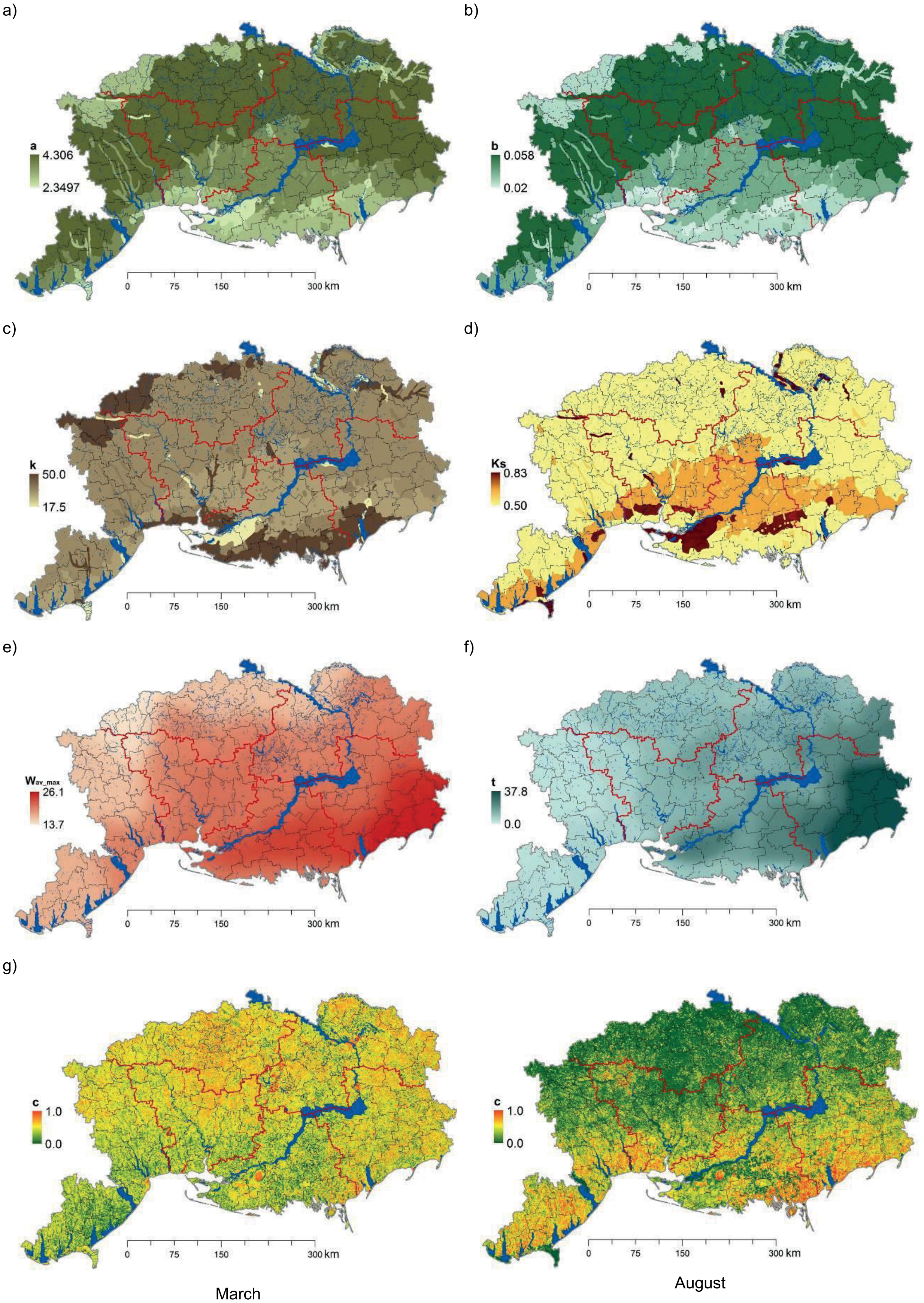

Fig. 5. Spatial distribution of factors of the deflation process in the steppe zone of Ukraine: a), b) coefficients that depend on the genesis, granulometric composition, density and other soil properties (*a*, *b*); c) clodding of the surface soil layer (*k*) (%); d) destruction coefficient of the aggregates of the surface soil layer (K_s); e) average maximum wind speed during dust storms of the 20th occurrence (W_{av_max}) ($m \cdot s^{-1}$); f) average number of hours involving wind erosion effect per year (*t*); g) coefficient of deflation resistant efficiency of the crop or crop rotation (*c*); source: own study

varies from 0 to 1 (Fig. 5g). As a result of GIS modeling using the potential soil loss model due to deflationy processes in clean steam areas (in absence of erosion control activities), soil losses in the middle of dust storms range from 0.02 $Mg{\cdot}ha^{-1}$ to 598.3 $Mg{\cdot}ha^{-1}$ [Dudiak *et al.* 2020].

Potential soil losses are reduced 5.62 times in conditions of the anti-deflation crop or crop rotation by factor *C*' comparing with the model assuming the absence of anti-deflation measures (Fig. 6a).

It was determined that about 40% of agricultural land is exposed to strong and very strong deflation processes. The land is mainly located in central and southeastern parts of the steppe (Fig. 6b).

Based on raster models of soil loss ($Mg{\cdot}ha^{-1}$) due to water (Fig. 4e) and wind (Fig. 6a) erosion, the raster model was created for the spatial differentiation of the total water and deflation steppe soil destruction (Fig. 7a). The distribution of agricultural land by erosion risk is shown in Table 4.

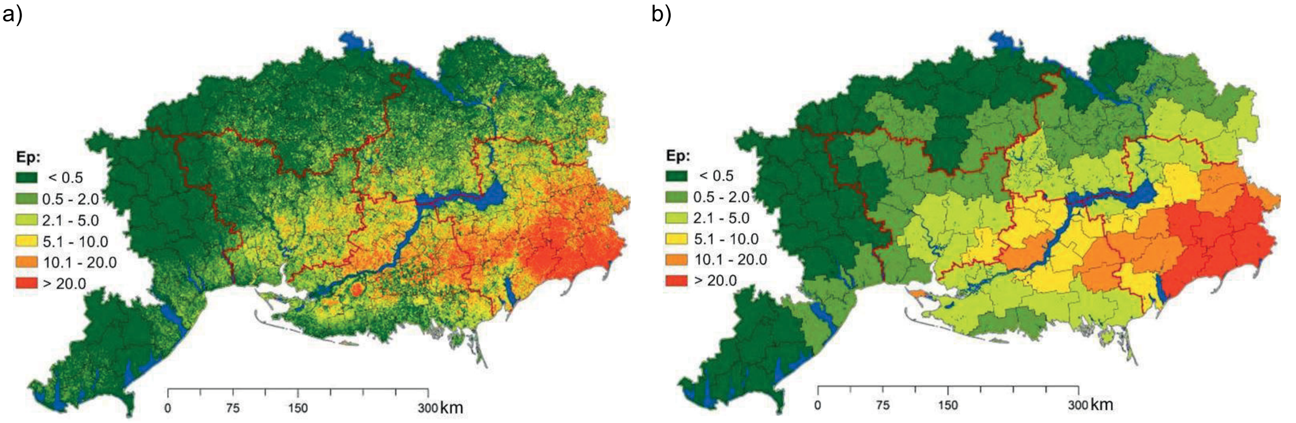

Fig. 6. Modeling the spatial distribution of potential deflation soil losses ($Mg{\cdot}ha^{-1}{\cdot}y^{-1}$) in the steppe zone of Ukraine: a) the spatial distribution cartogram; b) the average value for administrative-territorial districts; source: own study

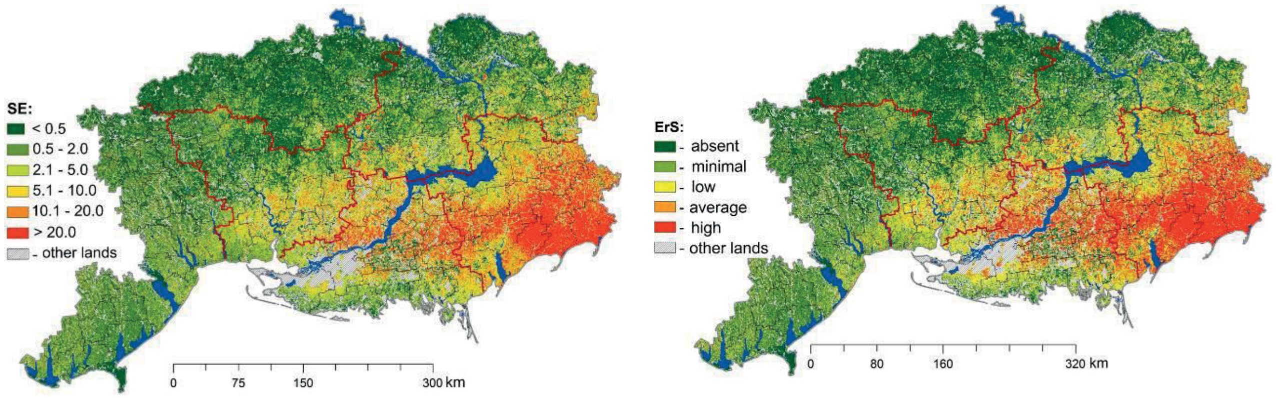

Fig. 7. The spatial distribution of total soil loss ($Mg{\cdot}ha^{-1}{\cdot}y^{-1}$) due to water and deflation destruction of soils in the steppe of Ukraine: a) total destruction of soil (*SE*); b) degree of soil erodibility (*ErS*)

Table 4. Distribution of arable land according to potential risk of water and deflation soil destruction

Erosion hazard	Soil loss ($Mg{\cdot}ha^{-1}{\cdot}y^{-1}$)	Degree of erosion development [Dudiak *et al.* 2020]	Area (thous. ha)	Percent area (%)
Conventionally absent	<0.5	I category	4 119.2	31.3
Minimum	0.5–2.0	II category	3 048.4	23.2
Low	2.1–5.0		2 404.5	18.3
Medium	5.1–10.0	III category	1 531.0	11.6
High	10.1–20.0	IV category	1 070.1	8.1
Very high	>20.0		988.9	7.5
Total			**1 3162**	**100**

Source: own study.

The conditionally erosion-safe land (31.3% of total arable land) includes the plain and the buffer borders of watersheds with vegetation (bio- and agrocenoses). About 68.7% of arable land is constantly under the influence of combined erosion processes, in particular: minimum and low impact discovered in 41.5% of the area, average impat in 11.6%, high and very high in 15.6% of the arable land.

It was determined that in the absence of environmentally justified erosion control measures, the degradation of soil increased as charactarised by the erodobility indicator. In particular, land in the low eroded category became medium or highly eroded (Fig. 7b) due to the loss of the most fertile layer of soil, removal of humus (dehumification of soil) and nutrients, significant deterioration of soil physical properties and, ultimately, a decrease in crop yields. With the deterioration of agrophysical properties of soil, its propensity to erosion increses, which can lead to a complete loss of humus horizon and irreversible deterioration of the soil.

It was determined that over the last 40 years the area of eroded land in Ukraine has increased by 2.5 mln ha. Thus, eroded land annually expands by 60–80 thous. ha. In 1960–2015, the area of eroded soil increased by 30–35%; the area of highly washed out soil increased by 20%; low – and medium washed out soil increased by 2 and 12%, respectively [Baliuk *et al.* 2010]. The area of little eroded arable land in the steppe is 2.2 mln ha (16.8% of arable land), whereas medium and highly eroded land occupies 2.9 mln ha (22.1%) (Tab. 5).

The soil infiltration capacity decreases to 30% in medium and highly eroded land and washing out increases by 1.5–2.0 times, which leads to the accumulation of erosive destruction products in soils. These products include agricultural chemicals, nutrients, heavy metals, including radionuclides. As a result, the quality of surface waters significantly deteriorates, eutrophication of the waters is stimulated, silting of small rivers progresses, and such small rivers gradually disappear.

The increase in eroded soil areas determines the degree of territorial ecosystem degradation (units) and makes it necessary to implement appropriate erosion control and land improvement measures. It is necessary to compensate the loss of humus to restore the fertility of eroded soils. Therefore, it is necessary to produce three times more organic matter than humus which has been washed away, as no more than 25–30% of the volume of organic fertilizers and green manure is humified [Barvinsky, Tikhenko 2015].

The organisational component of the rational agricultural land use is the zonal soil bonitation, which provides a universal evaluation of fertility when comparing agroclimatic conditions, the establishment of agriculture intensity to ensure the effective and environmental friendly production with the optimum use of the soil potential. Bonitation describes zonal soil characteristics as media for favorable plant growth, which is shown by quantitative fertility indicators expressed in points (from 0 to 100). The points can be calculated according to soil properties and climatic conditions. The main factors include the content of humus, humus layer, granulometric composition, macronutrient content, moisture content, total active temperatures and other. It is necessary to consider all, even vague relations, in particular, the influence of the terrain, as the total integral function that defines the process of redistribution of heat and moisture in soil. It largerly determines the yield of crops.

Bonitation of soil is a logical continuation of integrated studies on land and state cadastral assessment of agricultural lands. As regards land relations, it is the basis for establishing land tax, rates, mortgages and rents, and relevant put-up prices at auctions. It is also used in other areas related to land management, ecological-economic assessment of soil cover degradation and depletion of agricultural crops according to the erodibility of soils.

The main soil types of the region are chernozems. They take 83.2% of the total area of agricultural land, whereas chestnut and

Table 5. Influence of soil erodibility on the change of soil properties (properties and indicators of uneroded soil are taken as unit)

Property and indicator		Erodibility of soil				
		absent	minimum	low	medium	high
Agricultiral land	thous. ha	4 844.3	3 202.8	2 210.0	1 316.4	1 588.6
	%	36.8	24.3	16.8	10.0	12.1
Humus content		1.0	1.00–0.95	0.95–0.75	0.75–0.50	0.50–0.30
Lightly hydrolyzed nitrogen		1.0	1.00–0.95	0.95–0.80	0.80–0.66	0.66–0.50
Mobile phosphorus		1.0	1.00–0.82	0.82–0.70	0.70–0.60	0.60–0.40
Exchangeable potassium		1.0	1.00–0.91	0.91–0.85	0.85–0.80	0.80–0.70
Bulk weight		1.0	1.00–1.03	1.03–1.05	1.05–1.10	1.10–1.23
Moisture of plant wilting		1.0	1.00–0.96	0.96–0.90	0.90–0.85	0.75–0.65
Porosity (according to Zaslavskiy [1983])		1.0	1.00–0.95	0.94–0.90	0.90–0.80	0.80–0.75
Full moisture capacity (according to Zaslavskiy [1983])		1.0	1.00–0.98	0.98–0.95	0.95–0.80	0.80–0.70
Average yielding capacity of crops:						
– grain		1.0	1.00–0.85	0.85–0.80	0.80–0.60	0.60–0.30
– herbage		1.0	1.00–0.95	0.95–0.90	0.90–0.70	0.65–0.45

Source: own study.

dark-chestnut soil take 7.7%. Soil and climate bonitation is based on rasters of spatial distribution and involved four bonitation components in zonal soils: summary indicator of soil properties (*V*), coefficient of moisture (*HF*), coefficient of continentality of the climate (*CC*), and the average annual sum of active temperature above 10°C.

Depending on the soil type, the spatial differentiation of the aggregate indicator (*V*) is from 0.5 for sod sandy and chestnut alkalinized soils to 0.98 for typical chernozem (Fig. 8a).

calculate points of zonal soil bonitet for crops (Fig. 9a). It was determined that under the existing soil and climatic conditions in the steppe region, the bonitet points for growing crops vary from 20.3 to 72.1 points [DUDIAK *et al.* 2019b].

Adjustment was made to reflect negative processes of water and deflation destruction to the soil cover with a possible loss of grain crops (Fig. 9c). This clarified bonitet points (Fig. 9b).

As a result of the soil cover erodibility, a transition of about 23.3% of agricultural land from the category of high and medium quality to the category of medium, low and very low quality has been observed (Tab. 6). It leads to a loss of soil fertility up to 70%, a decrease in yield from 1 ha to 1.93 Mg (Fig. 9c) and, accordingly, a decrease in profit to 390 USD·ha^{-1} (Fig. 9d). The total yield loss per individual administrative and territorial units is from 10 to 500 Mg or more (Fig. 9e). It leads to agricultural loss of up to 100 thous. USD and more (Fig. 9f).

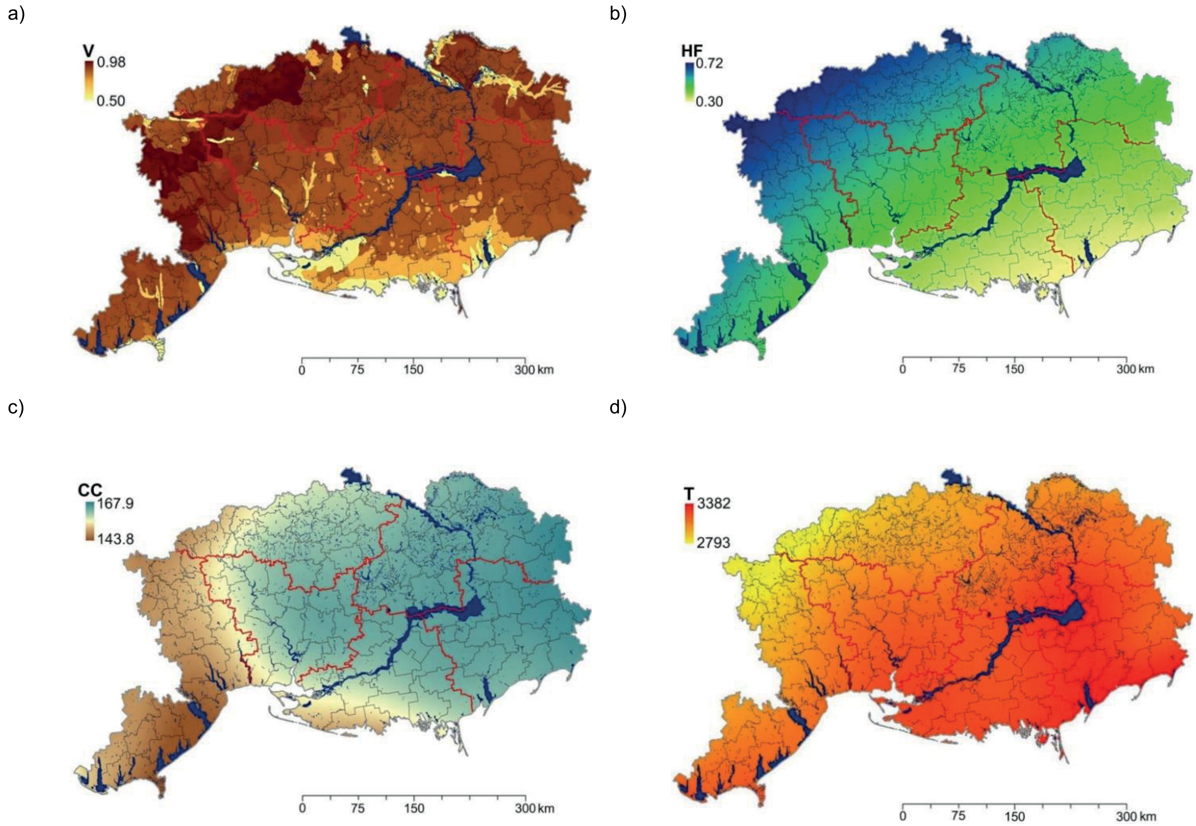

Fig. 8. Spatial distribution of soil bonitation factors on the territory of the stupa zone in Ukraine: a) summary indicator of soil properties (*V*), b) coefficient of moisture (*HF*), c) coefficient of continentality of the climate (*CC*), d) average annual sum of active temperature above 10°C; source: own study

The coefficient of moisture (*HF*) was calculated according to the method by IVANOV [1948] as the ratio of annual precipitation to annual evaporation for the relevant landscape, which is a ratio of heat to moisture (it helps to distinguish zones that provide biocoenosis with moisture). In the steppe region concerned the value of *HF* decreases from north-west to south-east from 0.72 to 0.30 (Fig. 8b). The reverse process is characterized by an increased continentality of the climate (*CC*). It characterizes a high amplitude of the air temperature, low rainfall and weak winds. On the territory of the steppe region, value *CC* is within 143.8–167.9 (Fig. 8c). Bioclimatic potential of agricultural production is largely associated with solar radiation, biochemical accumulation and migration of substances in soil, which are especially evident in the frost-free period when the air temperature is above 10°C. The average annual sum of active temperatures in the studied area increases from north-west to south-east from 2793°C to 3382°C (Fig. 8d).

As a result of the GIS modeling and soil and climatic models, the Raster Calculator in ArcGIS 10.1 was used to

Distribution of areas in the steppe region according to the crop loss and a decrease in profit per 1 ha of agricultural land are shown in Table 7.

The spatial differentiation of wheat yield losses in financial terms was determined according to data from the Food and Agriculture Organization (FAO) of the United Nations regarding export value of 1 Mg of grain for countries of the European Union as of November 2019, which was USD 202.25 [FAO 2019].

It was determined that the total yield loss due to water and deflation destruction in the Ukrainian steppe zone is about 15.11 thous. Mg, which translates into USD 3.05 mln.

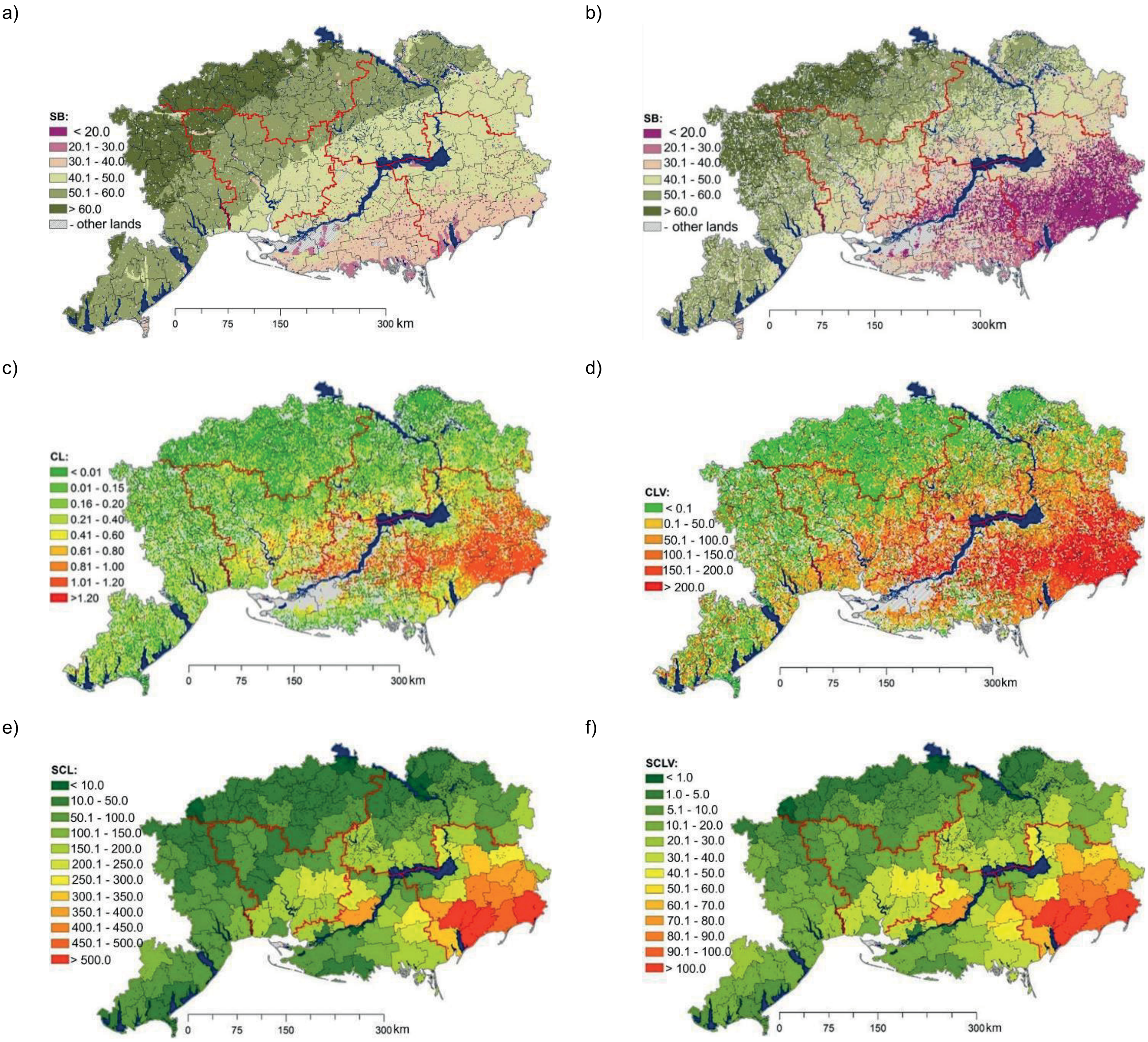

Fig. 9. Economic consequences of water and deflation destruction of soils in the steppe zone, Ukraine: bonitet of soil for growing of crops (*SB*): a) excluding erosion destruction, b) including erosion destruction; c) spatial differentiation of wheat yield loss ($Mg \cdot ha^{-1}$) (*CL*); d) spatial differentiation of losses (*CLV*) ($USD \cdot ha^{-1}$); e) gross losses of wheat yield (*SCL*) (Mg); f) total crop loss (*SCLV*) (thous. USD); source: own study

Table 6. Distribution of agricultural land areas according to soil and climatic potential and erosion destruction of soil

Soil quality	Point of bonitet	Distribution excluding erosion destruction of soils		Distribution including erosion destruction of soils		Replacement (%)
		area (thous. ha)	specific weight (%)	area (thous. ha)	specific weight (%)	
Very low quality	10.1–20.0	–	–	1 488.7	11.3	+11.3
Low quality	20.1–30.0	181.9	1.4	965.8	7.3	+5.9
	30.1–40.0	1 531.6	11.6	2 326.6	17.7	+6.1
Medium quality	40.1–50.0	4 653.5	35.4	3 026.3	23.0	–12.4
	50.1–60.0	4 744.5	36.0	3 732.5	28.4	–7.4
High quality	> 60.0	2 050.5	15.6	1 622.1	12.3	–3.3
Total		13 162	100	13 162	100	–

Source: own study.

Table 7. Distribution of agricultural land according to yield loss and material losses

Yield loss ($Mg \cdot ha^{-1}$)	Area (thous. ha)	Percent area (%)	Material loss ($USD \cdot ha^{-1}$)	Area (thous. ha)	Percent area (%)
<0.01	4 932.2	37.5	<0.1	4 932.2	37.5
0.01–0.15	213.2	1.6	0.1–50.0	3 150.1	23.9
0.16–0.20	1 678.2	12.8	50.1–100.0	1 952.0	14.8
0.21–0.40	2 148.5	16.3	100.1–150.0	1 346.4	10.2
0.41–0.60	1 586.2	12.1	150.1–200.0	311.6	2.4
0.61–0.80	924.6	7.0	>200.0	1 469.7	11.2
0.81–1.00	232.9	1.8	**Total**	**1 3162.0**	**100.0**
1.01–1.20	1 245.3	9.5			
>1.20	200.9	1.5			
Total	**13 162**	**100**			

Source: own study.

The environmental and economic assessment of damage due to soil erosion is characterized by quantitative indicators, in particular: the area of deflation land washed out and destroyed by ravines; layer thickness, volume and mass of lost soil; applied microelements (humus, nitrogen, phosphorus and potassium) into soil; amount of organic and mineral fertilizers for the restoration of eroded soils, increase of agricultural crops in the sowing due to their partial washing off and blowing off, increase in the resources for cultivating of eroded lands due to increase in the soil resistivity and short rutting, cost of gross crop output from eroded lands, increase in the direct cost related to the elimination of erosion consequences, structure of direct land improvement cost of eroded lands and financing direct salaries and other costs [Dudiak *et al.* 2019a, b; 2020; Lisetskii *et al.* 2012].

In order to protect soils from degradation, increase their fertility and crop yields in the Ukrainian steppe zone, it is necessary to implement adaptive and landscape erosion control design with elements of soil-protective agriculture, while taking into account the spatial differentiation of soil quality for growing crops (Fig. 10a) and categories of effects of erosion hazard of degradation of soil (Fig. 10b).

Soils of high quality account for 12.3% of arable land. They are well supplied with nutrients, and have favorable physical, chemical and agrophysical properties. The soil of lower quality shows negative properties and occupy plains and slightly inclined areas. They are suitable for mechanized cultivation, provide stable harvest of zonal crops. Agricultural land of average quality prevails in the steppe region. It occupies 51.4% of arable land. It has an average supply of nutrients and productive moisture. It shows negative properties (weak and average degree of acidity, alkalinity, etc.) and technological properties (division with network of beams, absence of shelter belts and buffer strips of natural vegetation, signs of erosion, etc.). Soils of low quality account for 25.0% and they have a low supply of nutrients, insufficient reaction to soil solution, water, air and thermal regimes, medium and highly negative properties, technological peculiarities of land plots due to a significant erosion tendency, and limited suitability for growing crops. They require systematic use of high doses of fertilizers, as well as land improvement and erosion control measures. Low quality soils account for 11.3% of arable land. They show low productivity with very low availability of nutrients, poor water and air and thermal regimes, and clear negative properties. They are also affected by significant erosion processes, are located on steep slopes, unsafe natural vegetation and forest belts, and are unsuitable for mechanical processing. Here, satisfactory yields are possible provided high doses of fertilizers are applied. It is necessary to provide integrated land improvement schemes and implement adaptive-landscape

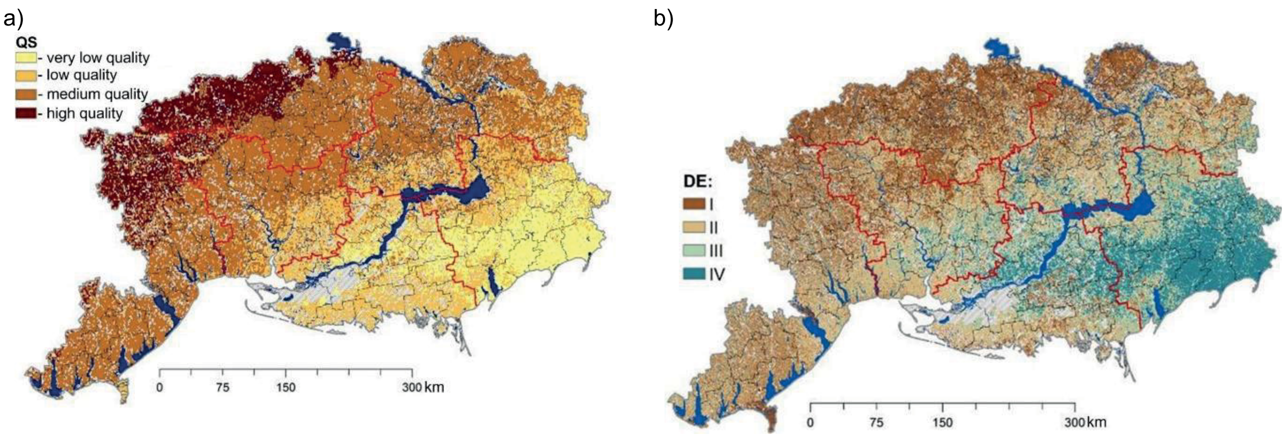

Fig. 10. Spatial differentiation of: a) soil quality (*QS*), b) soil erosion hazard category (*DE*); source: own study

erosion control measures, including elements of conservation farming.

Due to the intensive influence of water and deflation, the degradation of soil and agricultural land in the Ukrainian steppe can be divided into four erosion hazard categories (Fig. 11b). Accordingly, it is necessary to implement the adaptive and erosion-prevention control design, including elements of conservation farming: category I covers land that is affected by erosion, soil loss is conditional (no less than 0.5 $Mg \cdot ha^{-1}$); category II covers land with minimal and low erosion, soil loss of 0.5–5.0 $Mg \cdot ha^{-1}$; category III covers land with an average erosion risk, soil loss is 5.1–10.0 $Mg \cdot ha^{-1}$; category IV covers land that is affected by high and very high erosion, soil loss is 10.1–20.0 $Mg \cdot ha^{-1}$ or more. For category I of agricultural land with specific area of 31.3%, it is recommended the use zonal agricultural measures, including preservation and restoration of shelter belts; for category II of 41.5%, it is recommended to apply simple erosion control measures, i.e. optimal timing of tillage, fertilizing, snow retention, nonmoldboard cultivation and planting with preservation of the stubble on the soil surface, location of crop and convertible husbandry in strips of width 100–200 m and perpendicular to the direction of wind erosion threat, additional establishment of shelter belts; for category III (11.6%), the same activities should be performed as for the land of II category including additional nonmoldboard cultivation and sowing with maximum preservation of stubble, creating belts of tall crops, band placement of crops and convertible husbandry in combination with buffer strips of perennial grasses, establishment of a system of shelter belts; for category IV (15.6%), it is recommended to apply the entire complex of erosion control activities, including introduction of soil-protective crop rotations with dominating perennial grasses in the crop rotation, nonmoldboard cultivation and sowing with maximum preservation of stubble on the soil surface, complete grassing of slopes against wind, application of crops, convertible husbandry and buffer strips with perennial grasses in strips of width of 50–100 m perpendicular to the direction of wind, and the creation of a dense network of forest belts.

For the formation of environmentally sustainable agricultural landscapes and the decrease in erosion and cumulative processes in the zone of steppe of Ukraine, it is necessary to carry out the scientific spatial differentiation of systems depending on organizational-economic, agro-technical, forest improvement, hydro-technical and melioration measures that are aimed at rational use of land resources, preservation and raising of soil fertility, restoration of productivity for better use of all biological possibilities of territorial and aquatic ecosystems.

CONCLUSIONS

The spatial differentiation of environmental and economic effects of water and deflation destruction of the Ukrainian steppe was carried out using GIS and remote sensing technology. It was found that about 68.7% (8818.5 thous. ha) of arable land is constantly affected by the combined action of erosion, whereas the area of low eroded arable land is 16.8%, medium and highly eroded land is 22.1%. Due to erodibility of the soil cover, about 23.3% of agricultural land transferred from the category of high and medium quality to the category of medium, low and very low quality, which is caused by the loss of soil fertility up to 70%, reducing the yield from 1 ha from 0.05 to 1.93 Mg. The profit of agricultural producers decreased to 390 $USD \cdot ha^{-1}$, whereas direct costs increased due to use of eroded lands and violation of food security in the regions of the Ukrainian steppe. Gross yield losses in particular administrative and territorial units vary from 10 to 500 Mg and more, which translates into USD 100 thous. It was established that the total loss of crops due to water and deflation deterioration of agricultural land in the Ukrainian steppe zone was about 15.11 thous. Mg, or USD 3.05 mln. To protect soils, increase their fertility and productivity of agricultural crops in the Ukrainian steppe zone, it is suggested to apply an adaptive and landscape erosion control design with elements of conservation agriculture.

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