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Soil erosion by assessing hydrothermal conditions of its formation

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ABSTRACT

Soil erosion is one of the vital factors contributing to loss of fertility and environmental degradation. Generally accepted diagnostics of eroded soils is based on comparison of the sloping soils profile depth with the watershed soils. In this case, there is a separation problem of slope soils with a naturally shortened profile and eroded soils. Formation of the soil's natural profile on the slopes, caused by the action of natural factors of soil formation, can be described using a mathematical model, characterizing hydrothermal conditions of the slope areas through relative parameters of insolation (Ki) and moisture. These parameters describe the difference in soil formation conditions on the slopes from the upland areas. They are calculated based on the landforms parameters – incline and slope exposure. Their ratio, xeromorphy coefficient, can be used to forecast humus content and profile thickness of non-eroded soils on the slopes. As studies have shown, for non-eroded chernozem soils of Ukraine, the parameter xeromorphy describes 49% of the profile thickness dispersion, while for eroded soils it does not depend on this parameter. Thus, this model of profile thickness P versus xeromorphy can be used to forecast the thickness of non-eroded soil for specific conditions. Deviation of the profile thickness from the forecast one can be considered as manifestation of erosion or denudation.

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INTRODUCTION

Soil erosion is recognized as one of the most dangerous soil degradation processes in the world (Borrelli *et al.*, 2017; FAO, 2015;). It leads to irreversible losses of soil fertility and is probably one of the most important sources of greenhouse gas emissions into the atmosphere (Kudeyarov, 2018). Potential soil losses have been assessed by the results of mathematical modeling of erosion processes, mapping the risk of soil erosion in the last decade both for the EU, and in other countries of the world (Biswas *et al.*, 2015, Bosco *et al.*, 2015; Liu *et al.*, 2018; Panagos et al., 2018; Yang, 2015). However, mapping of water erosion based on predictive models is still a very rough estimate of its actual risk. Moreover, it can be used in estimating real soil loss with great caution, as indicated by (Laflen and Flanagan, 2013). Despite the long history of soil water erosion research, existing estimates of actual soil erosion losses and, consequently, its damage are still very approximate (FAO, 2015; Telles, 2011). Thus, damage estimates from water erosion in the United States vary from tens of millions to 44 billion dollars, annual losses from erosion in the EU are, according to Montannarella *et al.,* 2007, 45.4 billion dollars. The estimated losses of soil from erosion in the world according to FAO, 2015 are from 20 to 50 Gt/year. Soil loss data though vary by an order of magnitude – from 20 to 200 Gt/year because of their inadequate assessment. In addition, assessment of water erosion contribution to the global C cycle is also very ambiguous today (Chernova *et al.*, 2018; Lugato *et al.*, 2018; Van Oost, 2007; Yigini and Panagos, 2016;). There is still no consensus on whether erosion leads to carbon sink or emission into the atmosphere, and moreover, the extent of erosion processes contribution to the carbon cycle has not been estimated yet. One of the major obstacles to an adequate assessment of real soil losses and the dynamics of soil carbon on sloping lands is inefficient technique for determining soil erosion. There are neither precise quantitative criteria for its assessment, nor clear methodology for separation of underdeveloped and eroded soils on the slopes. Moreover, in real conditions erosion processes on the slopes lead to the formation of a complex mosaic structure of the soil cover, including eroded, non-eroded and washed soils (Achasov, 2009; Smetanova and Šabo, 2010; Zádorová *et al.*, 2008, 2014). In accordance with most existing techniques (IUSS Working Group WRB, 2015; DMES, 2010), soil erosion is expertly evaluated on the basis of external signs, such as visual detection of erosion, scour or wash, reduction of the upper horizon thickness, its color, ratio of the soil horizons thickness. Quantitative criteria to determine soil erosion and its degree are either absent or extremely approximate. For example, in FAO, 2015 guideline for soil description it is proposed to establish the degree of erosion visually, without clear quantitative criteria. Similar approaches are used in Ukraine (DMES, 2010). As a rule, the standard of non-eroded soils is watershed soil, where, hypothetically, erosion processes are mild. However, the features of the slope soil formation are not taken into account here. In fact, even in the absence of erosion processes less humidified soils with a shortened profile can be formed on the slopes, which can be mistakenly diagnosed as eroded. Such sloping soils, unlike the eroded ones, have a reduced potential for carbon sequestration, since their humus content is close to optimal for the existing soil formation conditions. Climate aridization will further contribute to the weakening of carbon sequestration of such soils. Eroded soils are, in fact, under-saturated with organic carbon. They have a high potential for its sequestration. Achieving a neutral level of soil degradation currently subject to erosion, will contribute to resumption of humus accumulation processes in such soils and binding of atmospheric greenhouse gases. In addition, incorrect diagnostics of slope soils status leads to an inadequate assessment of soil erosion losses and errors in calculating the damage from erosion for slope areas. The widespread use of digital soil mapping methods, using remote sensing data, also requires development of an additional quantitative method for differentiating eroded and non-eroded sloping soils. As studies have shown (Achasov and Achasova, 2011; Zizala, *et al.*, 2018), the automated selection of eroded soils only on the data from remote sensing is inaccurate. To obtain the correct results both remote and ground methods should be used. At the same time, characteristics of the landforms can be successfully used to predict different soil parameters in various regions (Achasov, 2009; Achasov *et al.,* 2015; Cherlinka *et al.,* 2017, Mosleh, *et al.,* 2016, Silva, *et al.,* 2016; Ziadat, 2010). This study has been carried out in Donetsk and Kharkiv regions of Ukraine during 2002-2013.

MATERIALS AND METHODS

Characteristics of research sites

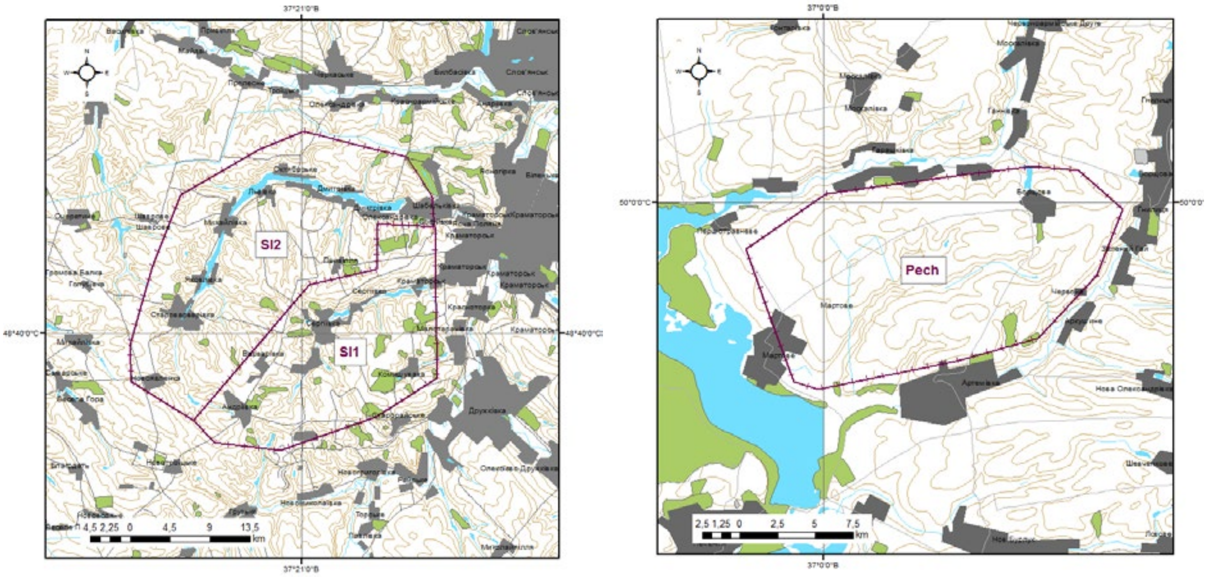
Soil studies were conducted on the territory of Ukraine, in the landfills located in Slaviansk district, Donetsk region (Sl1 and Sl2 landfills) (Fig. 1a) and in Pechenigy district of Kharkiv region (Pech landfill) during 2002-2013 (Fig. 1b). The total area of the surveyed territory is 43,500 ha. All the landfills are located in the Steppe zone. Prevailing soils of this area are (according to the Ukrainian classification) typical chernozems (Chernozems typical) and ordinary chernozems (Chernozems ordinary), formed on loess in a temperate continental climate. According to the FAO classification (IUSS, 2015), these soils belong to one group– Haplic Chernozems. Climatic conditions of the surveyed territories are described in details in the table (Table 1).

Characteristics of the studied soils

Studies in Slaviansk district were conducted on the territory of two landfills (Sl$_1$ and Sl$_2$, respectively), in the total area of 38,000 hectares (Table 1). During the survey, 135 soil sections were laid. In Pechenigy district, research was conducted on a landfill area of 4,500 hectares. 60 soil sections were laid in survey. The soils of all landfills were formed under conditions of a rather complex topography characterized by a developed ravine-gully network with significant differences in height (Table 1). This has caused a considerable development of erosion processes, leading to the complication of the soil cover structure.

Principles of sampling

The research methodology involved creation of a "training" sample", which included a large



a b

Fig. 1: The map of research territory in Donetsk region (a) and Kharkiv region (b)

Table 1: Study sites and their characteristics

Site	Physical and geographical area	R, MJ/м^2	D, days	T, °C	L, м	Vm, м	V, м
Sl$_1$ n=78	Western-Donetsk slope elevated	1800	160	+7,5	575	155	90
Sl$_2$ n=57	Western-Donetsk slope elevated	1800	160	+7,5	575	150	75
Pech n=60	Starobilsk slope elevated	1850	170	+8,2	550	140	60

* Note. R – annual radiation balance; D – frost-free period; T - annual average temperature; L – annual average precipitation; Vm – average height above sea level; V - height difference.

number of deliberately non-eroded soils, and a "working" sample, whose soils representatively characterize this territory as a whole and are eroded to varying degrees. Considering the fact that the very establishment of soil erosion in the field is a problem, it was necessary to find a sufficient number of non-eroded slope soils. The "training" sample was formed from cuts representing Slaviansk district. Landfills Sl_1 and Sl_2 were large areas and it was easier to find virgin areas or areas that had been removed from active use, without soil erosion processes. Consequently, it was possible to create two samples of soils (Sl_1, n = 78; Sl_2, n = 57), which with high probability were non-eroded and at the same time characterized the slopes of different steepness and exposure. Thus, Sl_1 and Sl_2 are samples of conditionally non-eroded soils. The convention in this case is explained by the fact that the territory of the Steppe zone of Ukraine has long been used by man for farming. Therefore, even the current virgin soils may actually be previously abandoned arable soils. The soils of Pechenigy District (Pech) were selected as the "working" sample, because according to preliminary estimates (analysis of the relief and Landsat satellite images) and field surveys they were characterized as the eroded ones. The soils of all landfills are quite similar but differ at the subtype level according to the Ukrainian classification (National report, 2010). Typical (Pech polygon) and ordinary chernozems (landfills Sl1, Sl2) vary in CaCO3 form in the parent rock, caused by the difference in hydrothermal conditions of soil formation. Table 3 shows characteristics of the studied soils. It is necessary to note that the table presents both complete samples (Sl_1, Sl_2, Pech) and samples of modal non-eroded soils (Sl_{1m}, Sl_{2m}, $Pech_m$). Modal non-eroded soils were considered the soils located on the watersheds, with surface slopes of less than 1 degree. At the same time, there were no signs of erosion processes on the ground (scour, signs of washing away and alluvial soil). In these conditions, in accordance with the methodology adopted in Ukraine, these soils can be described as non-eroded. Let us note that according to the methodology, all the other soils of these samples cannot be considered non-eroded, even in complete absence of visible signs of erosion. The soils of both landfills were formed mainly on loess deposits of similar granulometric composition (Table 2). The primary analysis of the table shows that the organic carbon content and soil thickness is slightly higher for the sample, representing the Pech polygon.

Field Soil Survey Technique

The locations of the soil cuts have been selected in accordance with the soil mapping methodology. The main principles are: 1) mandatory location of several basic sections in flat areas where erosion processes are absent or minimal, 2) sections located in virgin areas not subject to erosion, if possible, 3) sections in all major topographic elements. Field description of soil cuts was carried out according to the methods adopted in Ukraine. Soil samples were taken from the upper part of the genetic humus-accumulative horizon H from depth of 0–20 cm, in which the content

Table 2: Parameters of the studied soils

Site	SOC, %	Sand, %	Silt, %	Clay, %	P, см
Sl_1,n=78	4,87 (2,40-5,90)	17,62 (0,10-34,60)	35,06 (23,93-55,34)	47,31 (36,56-61,33)	76,05 (45-100)
Sl_{1m},n=10	3,11 (2,79-3,31)	12,85 (0,09-26,40)	42,08 (31,97-54,76)	45,80 (41,62-51,74)	91,00 (85-100)
Sl_2,n=57	4,74 (1,46-5,72)	15,70 (0,88-33,50)	44,42 (21,02-72,62)	39,87 (17,20-51,86)	74,91 (37-105)
Sl_{2m}, n=5	2,97 (2,85-3,26)	10,87 (8,44-12,58)	41,64 (38,02-63,69)	46,55 (27,82-51,39)	90,00 (86-105)
Pech, n=60	4,40 (2,43-6,16)	16,20 (1,15-32,61)	44,78 (29,50-60,88)	39,02 (24,52-52,82)	97,28 (34-168)
$Pech_m$,n=6	3,02 (2,52-3,17)	12,77 (5,03-18,10)	51,66 (35,96-55,20)	35,78 (33,28-45,93)	98,50 (83-110)

*Note. Sl_1, Sl_2, Pech - full samples; Sl_{1m}, Sl_{2m}, $Pech_m$ — samples of modal non-eroded soils; SOC_m — organic carbon content in the soil layer 0–20 cm,%; Sand - component of soil 0.05 to 2 mm in diameter; Silt - component of soil 0.002 to 0.05 mm; Clay - component of soil less than 0.002 mm; P - the thickness of the soil profile; The numerator indicates the arithmetic average value of the parameter (for Sl_{1m}, Sl_{2m}, $Pech_m$ samples - the median), in the denominator - the range of values.

of organic carbon and the particle size distribution of the soil were subsequently determined.

Geographical fixation of survey sites

Sites of all the cuts were recorded in space using GPS devices Garmin 12 and Magellan Explorist 500.

They were plotted on digital topographic maps of the surface on a scale of 1:10,000 in the ArcGIS10. The height above sea level, slope and surface exposure were determined.

Technique of hydrothermal conditions parameters

According to these values, the following topographic characteristics were calculated: insolation coefficient (Ki), relative wetting coefficient (Ku) and xeromorphic coefficient (Kk). Ki characterizes the ratio of the amount of direct solar radiation entering the real slope, compared with the amount of solar radiation on a horizontal surface, and is calculated according to (Achasov, 2006). Ku characterizes the ratio of the amount of water entering the soil on a given slope, compared with the amount of water entering the soil located on a horizontal surface. It is calculated according to (Achasov, 2009). The xeromophism coefficient is defined as the ratio of Ki to Ku. Based on the above, Kk characterizes the change in hydrothermal conditions of soil formation for a particular topographic area in comparison with a horizontal surface. Effectiveness of these coefficients has been proved in a number of studies (Achasov, 2006, 2009; Achasov and Achasova, 2011, Achasov *et al*., 2015)

Statistics

All obtained samples data were tested for normal distribution, basic descriptive statistics was calculated for all. The obtained data were processed by the following types of statistical analysis: the Kruskal-Wallis criterion, linear correlation, non-linear regression. Evaluation of the analytical predictive model was carried out using cross-validation. All statistical calculations were performed using the Statistica software.

RESULTS AND DISCUSSION

Comparison of non-eroded modal soils of landfills

The first step in the analysis of the obtained data was to check the quantitative data of the compiled samples of modal non-eroded soils (Sl_{1m}, Sl_{2m}, $Pech_m$. Because of difference in classification, basic parameters of the soils determining their invariant had to be unchanged. Analysis of samples for normal distribution (Table 3) has showed that non-parametric statistics should be applied to them. Comparison of three samples of non-eroded modal soils by the Kruskal-Wallis criterion (Kruskal-Wallis test) (Table 3) shows that they largely differ at the 5% level of significance only in the Clay parameter. Pairwise comparison of samples has showed that

Table 3: Results of a comparative analysis of modal non-eroded soils samples according to the Kraskel-Wallis criterion

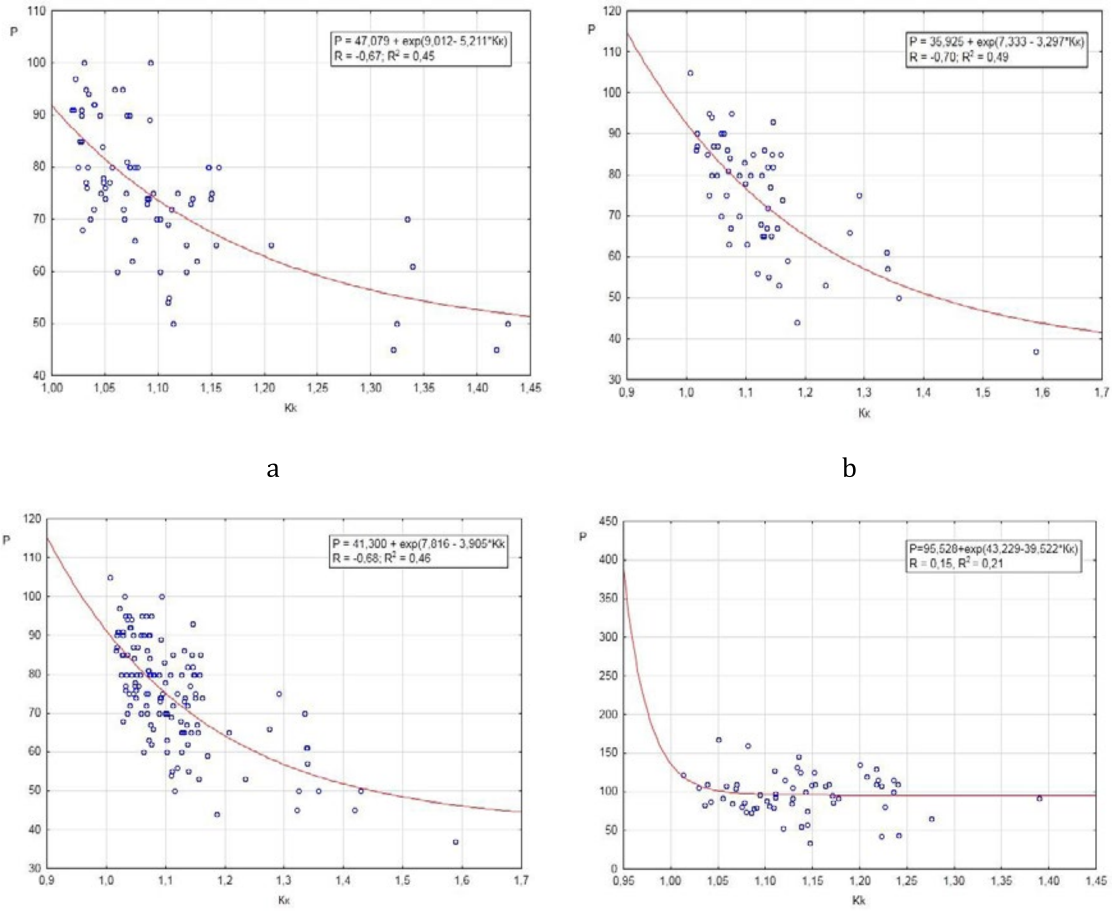
Variable	Samples	M	SR	MR	H	p
Sand	Sl_{1m}	12,85	114,00	11,40	1,605714	0,4480
	Sl_{2m}	10,87	38,00	7,60		
	$Pech_m$	12,77	58,00	11,60		
Clay	Sl_{1m}	45,80	147,00	12,70	4,848571	0,0885
	Sl_{2m}	46,55	55,00	11,00		
	$Pech_m$	35,77	28,00	5,60		
Silt	Sl_{1m}	42,07	83,00	8,30	3,591429	0,1660
	Sl_{2m}	41,63	55,00	11,00		
	$Pech_m$	51,66	72,00	14,40		
H	Sl_{1m}	42,00	107,00	10,70	11,66197	0,0029
	Sl_{2m}	39,00	22,00	4,40		
	$Pech_m$	45,00	102,00	17,00		
P	Sl_{1m}	91,00	101,50	10,15	1,032504	0,5968
	Sl_{2m}	90,00	50,50	10,10		
	$Pech_m$	98,50	79,00	13,17		
SOC	Sl_{1m}	3,11	126,00	12.60	1,781257	0,4104
	Sl_{2m}	2,96	55,00	11,00		
	$Pech_m$	3,01	50,00	8,33		

Note: M – median; SR – sum of ranks; MR – mean rank; KWT – Kruskal-Wallis test; H – H-statistics, p – level of statistical values.

significant differences are observed only for samples Sl_{1m} and $Pech_m$. The soils of the Pech landfill have a lighter grain size distribution and, as a result, a slightly more stretched upper genetic horizon. Differences in the soil profile thickness, the content of organic carbon and sand and silt in the soil layer of 0-20 cm, on the basis of statistical analysis, are recognized as insignificant. This suggests that the studied soils are genetically similar. The soils of the Pech landfill have a lighter grain size distribution and, as a result, a slightly more stretched upper genetic horizon.

Basic research hypothesis

It has been assumed that soils with a shortened profile are not always eroded. Such soils can be formed in natural environment as a result of a decrease in soil moisture on the slopes, associated with local hydrothermal conditions. First of all, this refers to the slopes of the southern exposure with significant steepness. Local dry conditions arise on such slopes due to: a) higher average annual insolation of the southern slopes and, consequently, greater evaporation of moisture from the soil, and b) a higher rate of water flowing down the slope and, as a result, less saturation (absorption) of moisture by the soil. Accordingly, by parameterizing influence of the relief factor, soil formation conditions in the local landscape were estimated. It is proposed to use the xeromorphy (Kk) coefficient as a parameter considering the effect of topography on soil formation.



a

b

c

d

Fig. 2: Dependence of the soil profile thickness (P) on the parameter Kk: a) for sample Sl_1; b) for sample Sl_2; c) for the combined sample Sl_1 and Sl_2; d) for sample Pech

Regression data analysis

Based on the above basic research hypothesis, the following scheme was adopted to analyze the obtained data: 1) building a dependence model of soils profile thickness on Kk, using the complete sample Sl_1; 2) cross-validation of the obtained model on the full sample Sl_2 data; 3) assessment of soil erosion degree of the Pech sample according to the proposed model. Before establishing regression links between Kk and P, normal distribution of these values over all samples was estimated. It has been found out that all the parameters under study are subject to the law of normal distribution, and standard regression analysis techniques are applicable to them. Regression analysis of the soil profile thickness dependence on Kk for sample Sl_1 has showed that it is exponential (Fig. 2a). To bring the exponential model to a linear one, the logarithm of parameter P was carried out. As a result, a formula of linear dependence of LnP on Kk was obtained, describing 47% of the soil profile thickness dispersion (Table 4).

The obtained model confirms the fact that soil formation on slopes essentially depends on the local features of the hydrothermal conditions. Difficulty in finding original non-eroded soils on the slopes should also be taken into account. It is likely that some soils in the sampling have weak manifestations of erosion, which cannot be clearly established by standard diagnostic methods. The received formula was verified by cross-validation on Sl_2 sample. The results have showed that the root - mean-square error (RMSE) value for the residual regression equation is 0.168. For comparison, the RMSE for Sl_1 sample was 0.1334 (Table 4).

The average value of the residuals module for Sl_2 sample after recalculation to centimeters is 8.7 cm. 95% confidence intervals of the average are 7.19 and 10.2. Average deviation of the predicted thickness of the soil profile for sample Sl_2 differs from the average value of the actual thickness of the soil by 8.7 cm. Transitions between all horizons of ordinary and typical chernozems are gradual and, according to the accepted method, the error in their determination in field conditions can be up to 10 cm. In general, the results of cross-validation confirm the high accuracy of the forecasting model. Fig. 2b shows relationship between P and Kk, obtained during the regression analysis of Sl_2 sample. This relationship is also exponential, which confirms the basic hypothesis. The obtained regression linear equation describes 51% of the thickness dispersion of the soil profile for sample Sl_2. Since the analysis has confirmed the consistency of proposed approach to the assessment of hydrothermal conditions of soil formation through Kk, samples of non-eroded soils Sl_1 and Sl_2 were combined (S_l). The analysis has showed (Fig. 2c) that the regression linear equation for the dependence of LnP on Kk for the combined sample describes 49% of the soil profile thickness.

Approbation of the resulting model

The next step in the analysis was application of the equation for the dependence of LnP on Kk, obtained for the combined sample of non-eroded soils on Pech sample. As it has been mentioned above, this sample, unlike the other two, represents both eroded and non-eroded soils. A preliminary analysis of the data has showed that there is no clear dependence of P on Kk (Fig. 2d) for this sample. Nonlinear regression analysis has showed that the exponential dependence model is estimated by a correlation ratio of 0.15, while all the regression coefficients are not significant at the 95% confidence level. The attempt to use linear regression for both P and LnP has not improved the result (Table 4). Forecast of LnP values from Kk, using the linear regression equation obtained for S_l sample, has showed large discrepancies between the predicted values of the soil profile thickness and the actual ones. The RMSE for residuals was 0.409, which is 3 times worse than the RMSE for the combined sample of non-eroded soils S_l. Average modular residual values for Pech sample after recalculation

Table 4: Regression dependency parameters

Site	Equation	R^2	RMSE	p-level
Sl_1,n=78	lnP = 5,8916 - 1,4355*Kk	0,47	0,1334	0,0000
Sl_2,n=57	lnP = 5,9425 - 1,4609*Kk	0,51	0,1432	0,0000
Sl, n=135	LnP = 5,895-1,4301*Kk	0,49	0,1381	0,0000
Pech, n=60	LnP = 5,088-0,4862*Kk	0,01	0,3029	0,0390

into centimeters was 30 cm. 95% confidence intervals of the average are 24.3 and 35.6. Thus, it can be argued that the average deviation of the predicted thickness of the soil profile for the Pech sample differs from the average value of the actual thickness of the soil by 30 cm. The obtained results indicate that the Pech sample soil profile thickness does not depend on the site of its location in the topography, which has been proved earlier. Thus, it can be concluded that majority of the soils in the Pech sample were eroded. Comparison of the actual values of P for each section with the calculated value of the soil profile thickness, obtained by the equation S_l, allows to determine the degree of its erosion. If the actual value of P lies within the limits of the confidence interval for estimating the average calculated value, then the soil under study is considered non-eroded. If P is greater than the upper confidence interval, the soil is washed, otherwise it is washed away.

CONCLUSION

The studies were focused on solving the problem of uncertainty in the diagnostics of short-profile slope soils. A shortened soil profile can be formed both as a result of natural environmental conditions, and as a result of exposure to erosion processes. The method for determining soil erosion based on a comparison of the actual thickness of its profile with the calculated value was proposed. The latter is determined on the basis of hydrothermal conditions formalization of soil formation through the coefficient of xeromorphy. In the course of the research it has been found out that the relationship between soil thickness and Kk has an exponential form for non-eroded soils located on various topographic elements. After reducing it to a linear form by logarithm P and carrying out regression analysis, it has been established that for a sample of 135 sections, 49% of P dispersion is described by Kk parameter. The correctness of the model was confirmed by cross-validation. The established model makes it possible to calculate soil profile thickness depending on the slope and exposure of the meta-cut of the section. Application of the model to a sample of eroded soils is expected to show large discrepancies between the actual P and the calculated P. Average deviation is 30 cm, which is about 1/3 of the modal non-eroded soil thickness located on the divide. According to the proposed hypothesis, soils with values below the lower confidence interval of the calculated value P are considered eroded. If P actually exceeds the upper confidence interval of the calculated P value, the soil is reclaimed.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percentage
Clay	Component of soil less than 0.002 mm
DEM	Digital Elevation Model
H	H-statistics
Ki	Insolation coefficient
Kk	Xeromorphy coefficient
Kw	Wetting coefficient
KWT	Kruskal-Wallis test
LnP	Natural logarithm P
M	Median
mm	Millimetre
MR	Mean rank
P	Profile thickness, cm
Pech	Full samples of Pechenigi landfill
$Pech_m$	Samples of modal non-eroded soils of Pechenigi landfill
p-level	Probability level
R^2	Determination coefficient
RMSE	Root-mean-square error
Sand	Component of soil 0.05 to 2 mm in diameter
Silt	Component of soil 0.002 to 0.05 mm
Sl_1	Full samples of Slaviansk1 landfill
Sl_{1m}	Samples of modal non-eroded soils of Slaviansk1 landfill

Sl_2	Full samples of Sloviansk2 landfill
Sl_{2m}	Samples of modal non-eroded soils of Sloviansk2 landfill
SOC_m	Organic carbon content in the soil layer 0–20 cm, %
SR	Sum of ranks

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