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Mapping soil erosion using magnetic susceptibility. A case study in Ukraine

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Abstract

The intrinsic element grouping of the magnetic susceptibility (MS) values is conducted. The relation between MS values and erosion index is shown. The objective of the investigation is study of the information about magnetic susceptibility of soils as a diagnostic criterion to erodibility. The investigations were conducted in the limits of Tcherkascy Tishki territory, Kharkiv district. The soils of the territory are presented by catenary row of chernozems. The study area was used in the field crop rotation. The soil conservation technologies have not been applied. The data analyze confirmed high correlation of the MS, erosive index and humus content. The possibility of MS cartogram using at the soil erodibility map is presented. The magnetic methods can be extensively used at the soil erosion investigations thanks to the speed and low cost.

1 Introduction

Soil erosion is one of the most important factors of soil soil degradation. Approximately 14 million ha (30 %) of Ukraine productive agriculture land is under influence of the water erosion (Bulygin et al., 1998). The known methods of the erosion study have significant disadvantages. The main ones are low productivity and high cost. The scientists are looking for new methods of the investigation due to the increasing of erosion investigation scope. The determination of land erodibility is the greatest challenge to specialists on soil conservation economic interests (during the planning of crop rotation, agrotechnical measures) and potential landowners (during the monetary value of land). Classification schemes of determination of land erodibility degree are based on these diagnostic criteria: the power of humus profile (soil profile), humus content (Surmach, 1992; Soil erosion, 2001) and alternative – content of biogenic compounds (elements) and soil parameters (Bulygin et al., 1998; Orlov et al., 1985). The investigation of eroded soils with classification schemes is possible using them in a single elementary soil area (ESA). Furthermore, the distribution of values of soil parameters

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can be represented as a strict monotone function, which used as a diagnostic soil characteristic along the profile (Bulygin et al., 1998).

Determination of etalon values of the soil parameters for the different degree of erodibility is doubtful. Using former Soviet Union models ("watershed", "slope", "virgin") do not describe fully soil structure of the slope and formalizes the multivariate soil formation (Lysetsky et al., 2012; Polupan et al., 2005; Shurikova et al., 1985).

Magnetic susceptibility is a good technique to measure soil erodibility (Lukshin et al., 1984; Vadunina et al., 1978). Magnetic susceptibility is the relation between value of induced magnetization of the sample with the value of this magnetic field. There are a few types of MS: volume (measured in the certain volume of matter), mass specific (measured in the certain mass of matter), and also frequency dependent magnetic susceptibility and anisotropy of magnetic susceptibility that are distinguished (Gubbins and Herrerobervera, 2007; Evans and Heller, 2003).

Information of soil magnetic properties is successfully used in several studies. The most studied branch of soil magnetism is environment protection. Previous studies carried out in Wales in England showed MS identified the majority of magnetic signals (Blundell et al., 2009). Gonzalez et al. (2002) observed also that magnetic properties of soils are changed due to migration of hydrocarbons, leading to the formation of second magnetic minerals.

Other studies about MS to measure soil erodibility were carried out outside Ukraine. In Bulgaria Jordanova et al. (2011) proposed to use the difference between MS of coarse and fine-grained mechanical fractions to estimate soil erosion. A detailed field and laboratory study on small 0.84 ha test site of agricultural land near Sofia (Bulgaria) has been carried out in order to test the applicability of magnetic methods in soil erosion estimation in the particular case of strongly magnetic parent material. Soil loss is estimated to be significant and mostly related to tillage practice. In Russia Lukshin et al. (1984) proposed to use the difference between the values of magnetic susceptibility for the diagnosis of soil erosion. The contents of magnetic spherules and ^{137}Cs and ^{210}Pb isotopes were determined in gray forest soils of the Novosil Agroforest

Experimental Station in Orel oblast (central part of European Russia) by Gennadiev et al. (2006). The spatial variability in the contents of these substances was studied and their distribution in the soil profiles and along soil transects within the afforested and cultivated slopes was analyzed. Recently Gennadiev et al. (2010) used the method of magnetic tracer to estimate the intensity of soil erosion and deposition of processes on slopes of different characteristics. The rates of erosion were determined for cultivated and virgin soils (predominantly, chernozems) on slopes in different parts of the United States and Russia. Quantitative parameters of soil loss and soil deposition for the slopes of different shapes and aspects were found. Specific features of erosional processes within different parts of slopes were revealed. Similar research was carried out in China (Wang et al., 2008). It was concluded, that variations in mineral magnetism, particle size, TOC and C/N of the 137Cs-dated sediments from Shibanqiao Reservoir revealed changes in soil erosion during 1960–2002. Most of the changes in relative intensity of erosion can be ascribed to fluctuations in precipitation. Changes in land use/land cover or human activities may account, in part, for changes in soil erosion inferred for four more roughly identified periods.

In agriculture, MS was applied to soils horizons characteristics and their physical properties (Semenov et al., 1998). Magnetic methods are also applied in other fields as soil moisture (Müller et al., 2009).

The aim of this paper is to study the information about magnetic susceptibility of soils as a diagnostic criterion of erodibility degree.

2 Materials and methods

2.1 Study site

The investigations were conducted at the areas of Tcherkascy Tishki, Kharkiv region, that is presented by catenary row of chernozems. The centre of the investigated area is 50.11° N, 36.43° E, 162 m a.s.l. The average annual air temperature is +7.9 °C, the

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amount of precipitation is 460 mm. Sampling area is presented with the north-facing slope, slope is 3–5°. The researched lands are used in the field crop rotation without special activities for soil erosion protection.

2.2 Soil sampling, laboratory analysis and soil indexes

The samples were collected in the top soil (0–20 cm) according to the scheme, represented on Fig. 1. After this the samples were grinded to a maximum size of 1 cm of soil aggregates. The samples were given to air-dry state. Each sample was weighted, situated in special box of volume 10 sm^3. MS measurements included mass specific investigations on KLY AGICO kapabridge and dual frequency MS2 meter on 2 frequencies (Operation Manual for MS2). We will describe shortly a motion of determination of soil MS: (1) samples of soil are without the action of enhanceable temperatures to air-dry condition; (2) it is determined specific magnetic susceptibility of the soil standards by kapabridge KLY-2 and magnetic susceptibility meter MS 2 (Operation Manual for MS2). The error of measurings during work from KLY-2 does not exceed 0,1 %. The total error is within 5 % (Menshov et al., 2012).

The soil humus content was determined due to the Ukrainian DSTU 4289:2004. The index of soil erosiodibility is the ratio of the average velocity of water flow in a particular part of agricultural landscapes to the speed of water flow which causes soil erosion (scouring velocity of a flow) by Kutsenko (2003).

The formula of the calculation for the sampling points is according to Kutsenko (2012):

$$I_e = K_p \frac{(kFI)^{0.4} J^{0.3}}{B^{0.4} n^{0.6} V_p}, \tag{1}$$

Where: K_p – is the coefficient of vegetation cover influence on erosion intensity; k – the coefficient of runoff; F – area of catchment of this stream, m^2; I – intensity of water flow, $m\,s^{-1}$; J – a slope of surface; n – a coefficient of surface roughness; B – a width of

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stream, m; V_p – erosion speed of water-course for plough-land, $m\,s^{-1}$. Erodibility risk: 0.0–0.5 – very low; 0.5–1.0 low; 1.0–1.5 – medium; 1.5–2.0 – high; > 2.0 – very high.

For statistical calculations the correlation analysis data was used. Checking the normality of the distribution was done with χ^2 method. Interpolation was carried out by the Nearest-neighbor interpolation. Cluster analysis was realized by Euclidean distance.

3 Results and discussion

3.1 Descriptive statistics

77 samples were used for measurements and data interpretation. As a result of the null hypotheses verification about the distribution laws of indicators it is revealed that the samples are characterized by complex histograms, for which it is impossible to determine the distribution laws. But for a part of the slope, which is characterized by high erosion danger for all three indicators laws of distribution are determined (Fig. 2).

In Table 1: χ^2 – the actual value of the verification criterion of the zero hypothesis about the distribution law, and χ^2_T – its tabular significance. For H is an average value and standard deviation of values $\ln H$.

On the basis of correlation and regression analysis the possibility of direct use as a diagnostic criterion erodibility soil MS is analyzed. The analyzed indicator with high probability is associated both with anthropogenic-natural distribution of the humus content ($r = 0.87; R^2 = 0.76$) and an index of the erosion risk ($r = 0.87; R^2 = 0.75$). Due to the linear dependence (based on limited sampling) between the content of humus and soil MS it is possible to directly use the schema of erodibility determination based on reduction of humus content. The linear correlation between the humus content reduction and soil capacity schemes are shown by Zaslavsky (1984). The parabolic schemes are presented by Shvebs (1981).

3.2 Spatial distribution of erosion index

As can be seen from Fig. 2, the points for which the laws of distribution are determined, are characterized by the values of an index of the erosion risk over 1.5. There were 41 of such points. Table 1 shows the parameters of the distribution. The points of high erosion index are located in Northen part of the area. The normal distribution low was established for MS values and eridibility index. The logarithmic normal distribution law was established for humus content.

The basic statistical characteristics and their erosion index distribution by values: > 1.5, 1.0 . . . 1.5 and < 1.0 are presented in Table 2. The main part of the investigated area is characterized by high and very high erodibility risk (> 1.5). The distribution law was established for this part. This confirms the reliable connection between the studied parameters for erosive index $I_e > 1.5$.

Capacity of a soil profile, humus content, soil MS are caused, on the one hand, by spatial combination of the factors contributing to the positive dynamics of soil formation – hydrothermal mode, maternal and underlain breeds (Menshov et al., 2012). On the other distribution of factors and conditions that stipulate the direction and intensity of processes that causes negative dynamics of soil erosion.

The relation between the soil erosion risk index, soil MS and humus content is shown in the Fig. 3. The obtained curves (third degree polynomial) can be divided into three segments, that are characterized by follows:

1. Optimality, uniformity of hydrothermal conditions on watershed part (the index of the erosion risk 0.5–1.0). Curve of researched indices is parallel to x-axis that indicates impossibility to describe by them the index of the erosion risk (graphic of function elasticity accepts a value close to zero);

2. Unidirectional changing of the values of soil MS and humus content as a result of changes in the hydrothermal regime in the range of the index of erosion danger 1.0–2.0. Function of elasticity accepts the maximum value;

3. Non-optimal hydrothermal conditions for humus formation and synthesis strongly magnetic minerals in the lower part of the slope in the range of index of erosion danger of 2.0–2.5. On this segment with the help of the humus content it is more possible to predict the index of the erosion risk in comparison with soil MS.

But the complexity of the relationships of these values is rather randomnicity than the functional dependence of indicators.

We propose the alternative approach to data analyze, which includes substantiation of the soil erosion structure of slope based on the spatial distribution of the topsoil MS values (Fig. 4a). The classes of soil MS were selected within 3 ranges of the erosion index risk: 0.5–1.0; 1.0–2.0; 2.0–2.5 (Fig. 4b). It was selected 13 classes of soil MS values for the index of the erosion risk (see Table 3). The clustering was realized by Euclidean distance method. It was obtained that range of erosion index 0.5–1.5 responds to the 2–4 classes of soil MS. Their average values are $794–750 \times 10^{-9}\,m^3\,kg^{-1}$. These soils are not eroded according to the classification of Zaslavsky (1984). Heterogeneity values range 1.0–2.0 indicates the development of rill erosion. The average values of classes (4–8) respond to MS values $750–593 \times 10^{-9}\,m^3\,kg^{-1}$. The areas with the lowest values can be attributed to the low eroded soils. The range of erosion index 2.0–2.5 characterizes medium eroded soils (classes 10, 11, 12). The MS values are $621–503 \times 10^{-9}\,m^3\,kg^{-1}$.

Maximum values of humus content for the investigated area are 4.41 %. According to the classification of Zaslavsky (1984) the humus content for not eroded soil is over 4.0 %, for low eroded soils – 4.0–3.5 %, for medium eroded soils – 3.5–2.2 %, for strongly eroded soils – less than 2.2 %. Strongly eroded soils have not been observed at the investigated area. The cluster analysis suggested the correspondence between soil erosion level, erodibility risk indexes and soil MS values.

4 Conclusions

The MS values of investigated soils were divided into 13 classes. They respond 3 classes of soil erosion.

Soil MS has a high degree of statistical relationship with erosion index and humus content. MS can be used to establish the erosion area. This technique has advantages over conventional: cost and rapidity. This is possible to form a dense grid of sampling ore, justify erosion structure of slopes.

More reliable results of soil erosion investigations can be obtained by complexation of magnetic and other methods.

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Table 1. The parameters of the distribution of indicators.

Indicator	Distribution law	χ^2	χ^2_T	Average value	Standard deviation
MS $\times 10^{-9} m^3 kg^{-1}$	Normal	3.6	6.0	617.2	38.2
H (humus), %	Lognormal	6.6	9.5	1.14	0.08
I_e (erosive index)	Normal	6.9	9.5	2.11	0.22

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Table 2. Statistical parameters of soil properties.

Data	Selection	Erodibility risk		
		> 1.5	1.0...1.5	< 1.0
Samples	77	48	11	18
MS (10^{-9} m^3 kg^{-1})				
Mean	686.05	635.13	747.58	784.25
Max	862.28	801.00	766.52	862.28
Min	499.33	499.33	729.17	745.16
Standard deviation	88.81	69.94	12.04	35.52
Variation coefficient, %	12.95	11.01	1.61	4.53
Median	692.19	630.09	745.11	785.02
humus content, %				
Mean	3.61	3.31	4.00	4.14
Max	4.41	4.19	4.24	4.41
Min	2.59	2.59	3.6	3.76
Standard deviation	0.51	0.41	0.23	0.18
Variation coefficient, %	14.22	12.40	5.75	4.38
Median	3.62	3.21	4.07	4.16
Erodibility risk				
Mean	1.61	2.03	1.35	0.67
Max	2.49	2.49	1.49	0.87
Min	0.47	1.53	1.18	0.47
Standard deviation	0.63	0.29	0.11	0.14
Variation coefficient, %	38.93	14.54	7.82	20.35
Median	1.77	1.98	1.37	0.67

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Table 3. Distribution of classes soil MS values within the erosion index ranges.

MS ($10^{-9}\,m^3\,kg^{-1}$)	Range of erosion index with number of points		
	0....1.0 (not eroded)	1.0...2.0 (low eroded)	> 2.0 (medium eroded)
855 ± 10.4	2		
794 ± 7.4	8		
757 ± 8.5	8		
750 ± 16.6		16	
703 ± 7.5		5	
675 ± 6.7		5	
646 ± 8.8		6	
593 ± 12.1		5	
673 ± 0.0			1
621 ± 9.0			8
589 ± 4.8			5
563 ± 9.8			6
503 ± 4.8			6

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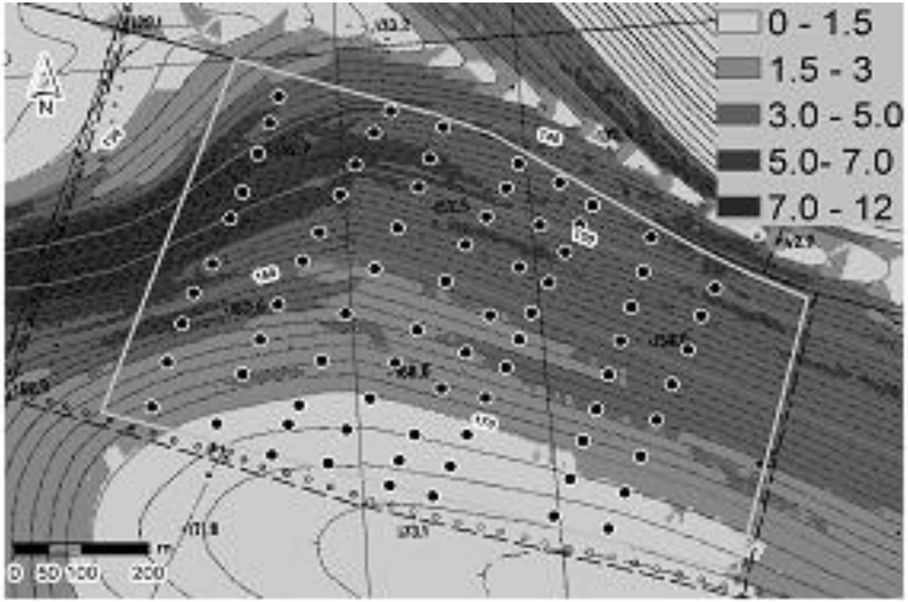

Fig. 1. Sampling grid and slope steepness (in degrees).

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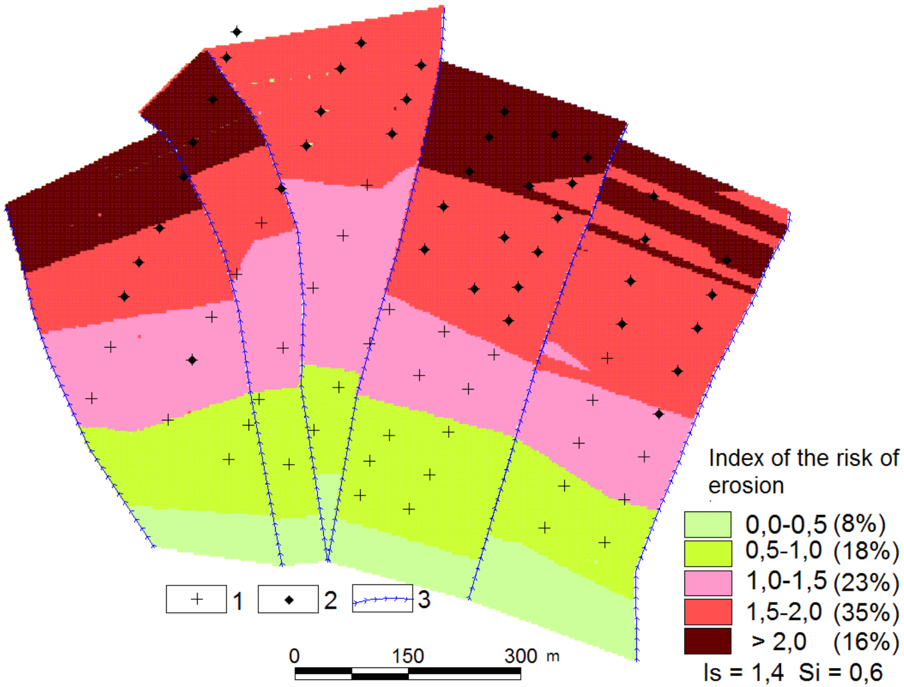

Fig. 2. Assessment of the lands erosion risk and location of sampling points: 1 – sampling points of the ground; 2 – points for which the distribution laws are determined; 3 – runoff line position; flow Is – the average value of the index of the erosion risk; Si – its standard deviation.

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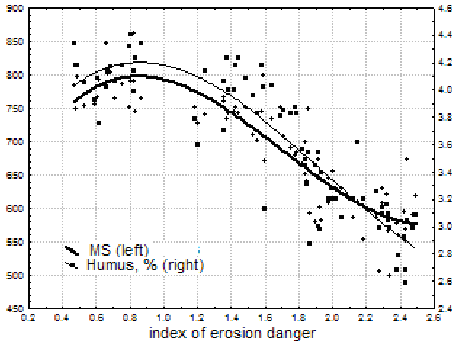

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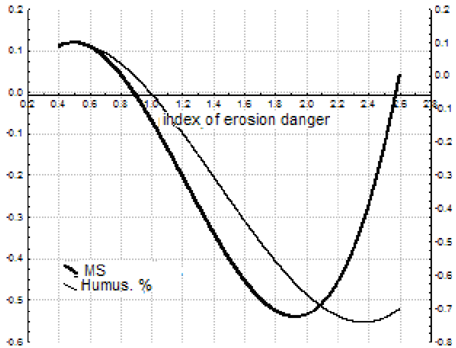

b

Fig. 3. (a) – Graphics of functions of dependence between the soil MS ($10^{-9}\,m^3\,kg^{-1}$), humus content (%) and the index of the erosion risk; **(b)** – graphic of elasticity of these functions (elasticity shows how the value of the function will change, if the argument increases by 1 %).

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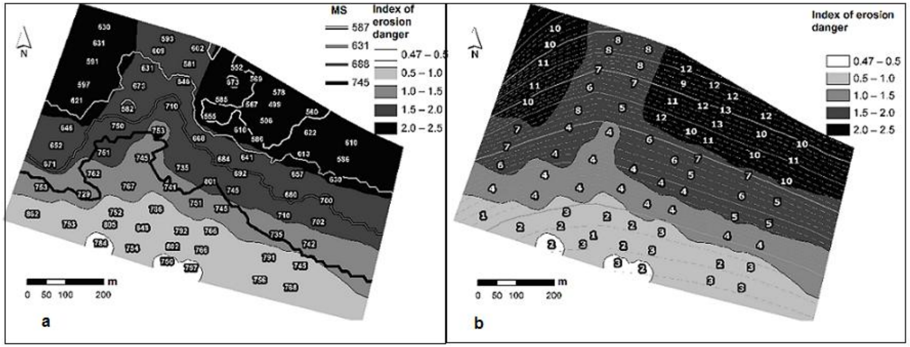

Fig. 4. Rationale of erosion patterns on the basis of the spatial distribution of soil MS: **(a)** – point values soil MS; **(b)** – classes of soil MS ($10^{-9}\,m^3\,kg^{-1}$) for the index of the erosion risk. Statistically the same samples are marked with appropriate color.

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