MODELLING AND MAPPING OF DIFFERENTIATION IN SOIL MATERIAL REDISTRIBUTION IN THE ARABLE AREAS

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ABSTRACT:

In the current article, we describe an approach to computational estimation of the soil runoff intensity in the experimental area. Additionally, we summarize most basic recommendations for the implementation of proposed approach when studying arable planes complicated by polygonal-block microrelief. These recommendations are aimed onto formalising and simplifying of the initial data preparation for automated GIS-based mapping of soil runoff. Particularly, we recommend to establish a reference value of caesium-137 deposit at the block elevations of watershed surface. As a result of the experimental work, we present map of caesium-137 deposit in the soil material and soil loss intensity map compiled automatically for the experimental area.

1. INTRODUCTION

Estimation of the soil loss spatial differentiation is demanded in soil and environmental studies and land management. It appears valuable also when implementing precision farming principles. Generally, soil loss estimation assumes multiple in situ at-a-point assessment of soil loss. Reliable techniques for indirect assessment and geospatial interpolation remain awaited for implementation in this domain.

One of promising approaches helping to ensure automation and indirect estimation of soil loss is the radiocaesium method (Walling, He, 1999). Anthropogenic origin caesium-137 deposit in the soil material (particularly Chernobyl origin caesium-137, accumulated in the soil after Chernobyl accident) can be applied as a soil loss (runoff) marker (Larionov, 1993; Litvin et al., 1996; Shamshurina et al., 2016; Maltsev et al., 2019). Caesium-137 of Chernobyl origin, being a marker of varying washout degree soils, allows identifying areas that are differ in the magnitude of the soil and topography erosion potential.

The caesium-137 allows reliable study of soil processes in more than last 30 years. The reliability of this approach is based upon that the caesium-137 (in opposite to potassium-40, for instance) is not a natural component of the soil and can be observed only in a result of nuclear pollution. This property of caesium-137 makes it possible to study the movement of chemical elements in the soil material and movement of soil material itself consequently. As it cannot be deposited accidentally in the soil horizon, a long-term study of its (re)distribution, makes it possible to track the soil processes (Mamikhin et al., 2016).

Our study is aimed onto development and verification of methodology for the automated soil loss intensity estimation in arable areas. We apply radiocaesium method and geomorphometric mapping to produce soil loss maps, which can be applied to land management purposes. The methodology is based upon the our own in situ data obtained in 2012-2020 on an experimental study area in the basin of Sukhaya Orlitsa River (Oryol district, Oryol region, European part of Russia).

The study area can be denoted as a plane complicated by polygonal-block landforms at watershed surfaces and ravines at slopes. We use in situ data to assess reference values of caesium-137 deposit, and to ensure accuracy control when providing geospatial interpolation of soil loss assessments. It is significant to underline that in the studied area a network of microstreams is presented that complements (in the meaning of runoff regime) the system of hollows and plowing furrows formed on the arable surface over many years of plowing along the slope. This network was not considered in current study, and requires separate consideration.

Today, researchers estimate at-a-point values of soil losses using various erosion models (Ivanov et al., 1990; Okulik, 2006; Savin et al., 2019; Ivanova, Burakov, 2020). In 2023 Zhidkin and co-authors verified the WaTEM/SEDEM set of rain erosion models in combination with the snowmelt erosion model of the Russian Hydrological Institute (Zhidkin et al., 2023). Researchers concluded that erosion models can underestimate the amount of soil loss up to 4 times. Based on the results of the study, the authors concluded that it is necessary to calibrate the parameters of the models for a specific study area. This conclusion suggests that a currently presented problem of objective experimental identification and delineation of characteristic areas in the studied territories having different conditions for the erosion process formation is observed, in addition to a problem of parameterizing needed for the models applied to account meteorological conditions.

Generally when study of soil morphology is applied to estimate soil runoff regime, a large number of soil samples have to be collected (Zhidkin et al., 2023). In order to form a detailed picture of erosional soil losses, it would be necessary (in our case) to form a network of sampling plots in the lower part of the slope of the southern exposure at the exit from each hollow, as well as at the exit of each plowing furrow and each microstream. Obviously, such a work would be extremely time consuming. However, the radiocaesium method was applied also as a method able to ensure integral accounting of soil runoff along slope disturbed by a complex system of erosion furrows.

2. DATA AND METHODS

Study area central point located at 53°0'22.9"N 35°57'12.30"E. Heavy gray forest loamy soils are common in the Orel region, where study area is located. The arable field where sampling and measurements were conducted can be considered representative

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for the left bank of the upper Oka within the Orel region. Sampling plots were assigned along the thalwegs of ravines and plowing furrows (at the time of sampling, plowing furrows were recognized in situ by characteristic longitudinal depressions in the topography surface). The assignment of soil sampling plots along the thalwegs of depressions was reasoned by using of catchment area value as a predictor for caesium-137 deposit estimation.

The catchment area is the potential above–located area from which soil can flow to discovered location (node of gridded map), and can be washed away through the location. According to the catchment area of the ravine increasing, soil runoff have to increase also, and have to be accompanied with the decrease in the caesium-137 deposit.

Our approach to radiocaesium method implementation assumes at-a-point estimating of soil loss value basing on comparison of at-a-point caesium-137 reserve in the soil material to the reserve at the reference plot (used as a benchmark value). Reference plot in this case is a location where the soil run-off is not observed, and caesium-137 deposit remains stable. The reference plot was allocated using mapping of geomorphometric parameters of the topography relief, particularly catchment area (Costa-Cabral, Burges, 1994; Shary, 2005) and profile curvature (Evans, 1972). Geomorphometric mapping was automated using ArcGIS and SAGA GIS software facilities. Soil runoff/accumulation values are estimated and spatially interpolated using ArcGIS ModelBuilder functionality. The digital elevation model (DEM) was produced using topographic map of 1:10,000 scale. Morphometric relief indicators were calculated using DEM using SAGA GIS software tools.

In addition, the catchment area and the sign of profile curvature value were interpreted jointly as an integral indicator of the topography erosion potential. The dependence of the activity of caesium-137 on the catchment area and the sign of the profile curvature were used as the basis when identifying zones in the study area different in the meaning of the soil runoff regime and soil/topography erosion activity.

Since it is not yet possible to take into account all the elements of the erosion network in the studied area, we were focused onto identifying the most characteristic zones in the studied arable field. Basing on catchment area value statistics, we identified manually seven specific zones in the studied arable area, where individual empirical computational models for the caesium-137 deposit assessment were demanded according to the differences in soil runoff intensity (Fig. 1). The statistical sample used for calibration of computational models was made up of sampling data collected in 2012-2020 (more than 500 samples in total).

Computational models (Fig. 2, Table 1) compiled for the delineated zones describe the dependence of (potential) deposit of caesium-137 in soil material on catchment area value separately for concave and convex sectors of the arable surface (detected according to the sign of profile curvature of the surface). The computational equations for ravines of 23,000 sq. m and 50,000 sq. m catchment area (zones 1 and 2 in Fig. 1), and for a zone of degraded soils (3 in Fig. 1) were presented earlier (Trofimetz et al., 2022b).

Zones 4-6 (in Fig. 1) were delineated additionally in 2023 basing on statistical sample formed in 2016-2017 (soil samples collected in the arable horizon of 0-25 cm). Caesium-137 deposit was estimated for each sampling plot basing on the results of gamma-spectrometric analysis of the sampled material. Gridded maps of the catchment area and profile curvature were used were recomputed into the map of caesium-137 deposit according to the developed empirical equations.

Figure 1. Experimental area in the basin of the Sukhaya Orlitsa River (Oryol region). Soil runoff zones are delineated by black lines and numbered. Satellite image courtesy of DigitalGlobe Foundation.

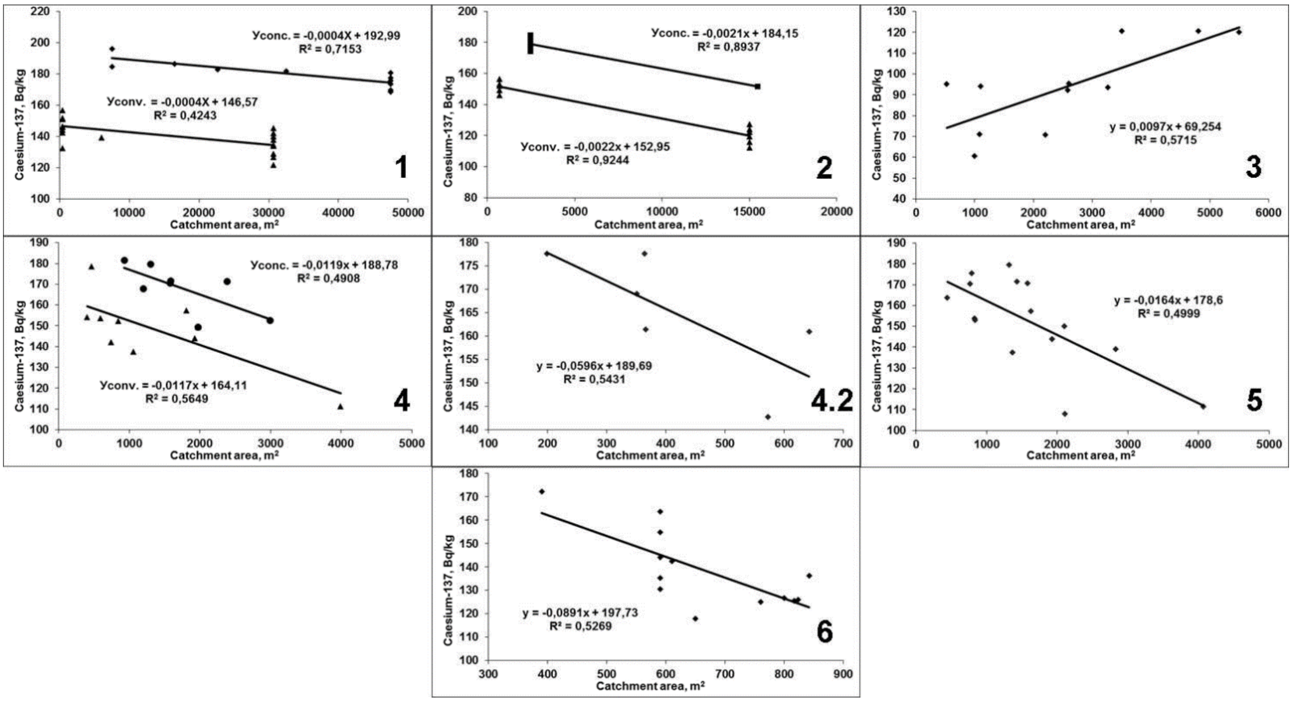

Figure 2. Computational models compiled for the soil runoff zones presented in Fig.1.

Soil runoff zone	Equation	Conditions needed for equation application			
		Catchment area	Topography surface exposure	Runoff/accumulation slope sector	Profile curvature sign
1	У = -0.0004X + 146.57 У = -0.0004X + 192.99	≤50000 ≤50000	Southern Southern	Runoff Accumulation	+ -
2	У = -0.0022X + 152.95 У = -0.0021X + 184.15	≤23000 ≤23000	Southern Southern	Runoff Accumulation	+ -
3	У = 0.0097X + 69.254	≤6000	Southern	Watershed/Degraded soils	
4	У = -0.0117X + 164.11 У = -0.0119X + 188.78	≤4200 ≤4200	Southern Southern	Runoff Accumulation	+ -
4.2	У = -0.0596X + 189.69	100≤500	Southern	Runoff	+
5	У = -0.0164X + 178.60	≤4200	Southern	Runoff	+
6	У = -0.0891X + 197.73	≤4200	Southern	Runoff	+

Table 1. Equations for used for estimation of caesium-137 deposit for the soil runoff zones presented in Fig.1.

3. RESULTS AND DISCUSSION

Visual analysis of very high resolution satellite imagery, estimation of the degree of arable surface disturbance by plowing furrows (which distort the picture of the natural soil erosion loss process formation), and study of the catchment area and profile curvature maps, together allowed us to delineate seven zones in the considered area of the agricultural field different in the meaning of erosion process features. The boundaries of the zones were allocated along the watershed lines, with the exception of zone 6. This zone covers a set of origins of the microdepressions in the slope bottom. Zone 1 covers the basin of the 50,000 sq. m catchment area ravine. Zone 2 covers a set of basins of the ravines with up to 23,000 sq. m catchment areas. Zone 3 cover a belt of degraded soils. Zone 4 composed by microravines with up to 4,200 sq. m catchment areas. Zones 4.2 and 5 are the separate surfaces where up to 500 sq. m catchment areas are observed.

Using pixel-by-pixel computations and compiled computational models, we produced the map of estimated (potential) distribution of caesium-137 deposit (Fig. 3), that was recomputed consequently (Trofimetz et al., 2022b) into map of soil runoff and accumulation intensity (Fig. 4).

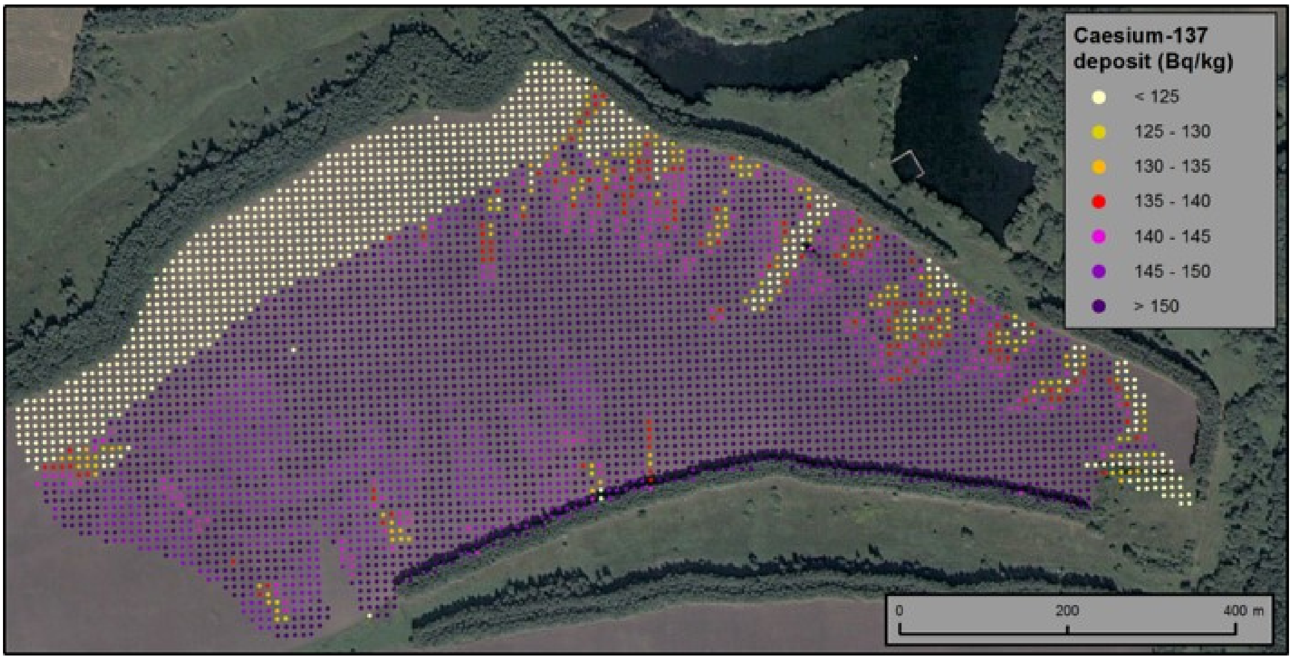

Figure 3. A map of the estimated caesium-137 deposit distribution. Satellite image courtesy of DigitalGlobe Foundation.

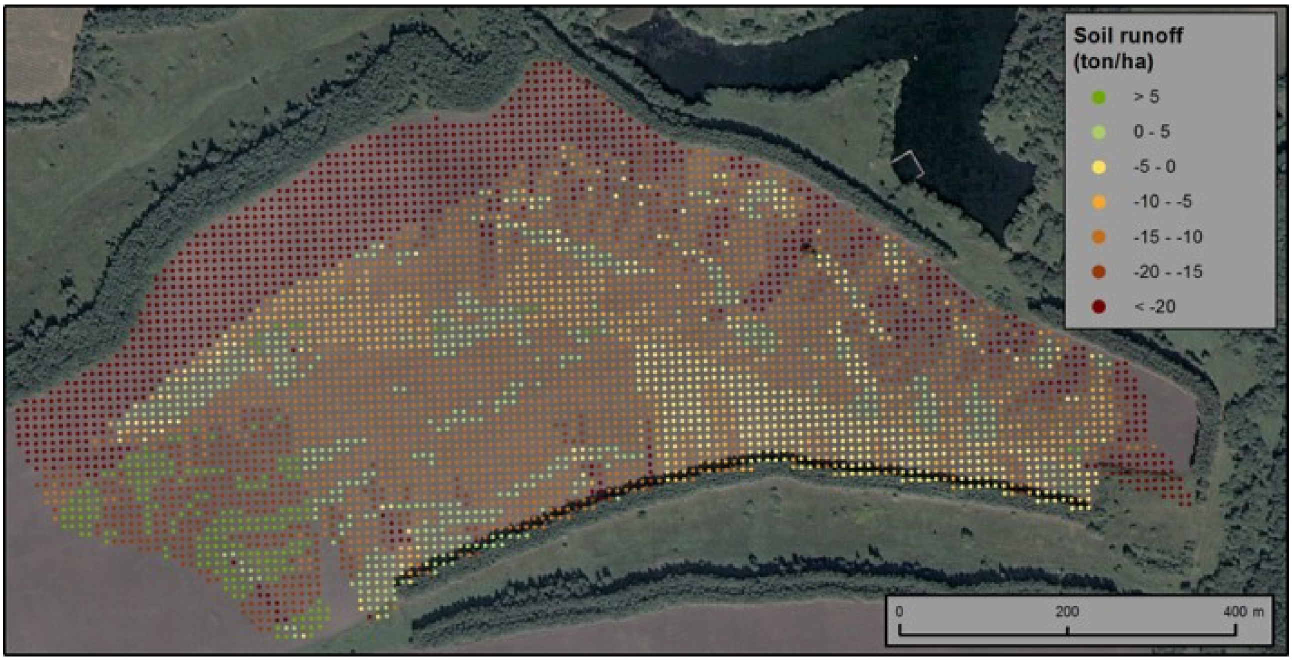

Figure 4. A map of the estimated runoff/accumulation intensity distribution in 1986-2016. Satellite image courtesy of DigitalGlobe Foundation.

It have to be underlined once again, that it was not always possible to recognize the thalwegs in the field, and it was also not possible to take into account all the elements of the erosion network on the studied slope. The overlay of sampling plots network onto the catchment area map area highlighted that not all the plots were allocated in the thalwegs. In some cases all the lengths of thalwegs were traced by sets of sampling plots, in some cases only upper part and(or) lower sectors of thalwegs were traced correctly.

The sectors of inwashed soil material (sectors of accumulation) were detected along the thalwegs using the profile curvature sign. In the cases when only solitary accumulation sectors were detected along the thalwegs, the profile curvature sign was not taken into account when compiling computational models for soil runoff zones.

Soil sampling and the gamma-spectrometric analysis of collected samples provided information necessary to compile empirical dependencies of caesium-137 estimations on morphometric variables within seven delineated zones. Simultaneously, the problem of the reference plot allocation on watershed surface was solved, where the benchmark value of caesium-137 deposit was estimated afterwards.

Earlier (Trofimets et al., 2022a) we found that the watershed surface in the studied area is composed of block elevations and interblock depressions, where soil runoff is possible. These landforms can be observed on very high resolution satellite images. Analysis of the catchment area map and caesium-137 deposit estimations made using the gamma-spectrometric analysis results, alongside with implementation of previously proposed recommendations on reference plot allocation within block elevations on watershed surface (Trofimetz et al., 2022a), allowed us to recommend delineation of a “minimum erosion belt” within the area where the 100-500 sq. m values of the catchment area are observed. The variability of caesium-137 deposit values within this belt is 0.3. This means that the set of samples collected in the area is homogeneous. However, observed dispersion is significant.

As the average values calculated from a homogeneous set of samples are significant, we believe that reference plots can be assigned within the minimum erosion belt. It was not possible to allocate an area within which the caesium-137 variability would be less. This task should be solved separately in the course of larger-scale studies.

Despite that for each soil runoff zone it is probably necessary to specify the caesium-137 reference value separately according to a diagram of the in-depth caesium-137 distribution (Shamshurina et al., 2016), at the current stage of our study we used unified reference value of caesium-137 deposit as 174.7 Bq/kg (Trofimetz et al., 2022b).

4. CONCLUSIONS

Conducted in situ observations and more than 500 collected soil samples made it possible to identify seven zones in the studied arable area that have different statistical relationship between the values of caesium-137 deposit and morphometric indicators (catchment area and profile curvature sign). The minimum erosion belt allocated in the zone of 100-500 sq. m catchment area values can be recommended for use when selecting the location for reference plots (the variability of caesium-137 deposit within the belt is no more than 0.3). Detection of the minimal erosion belt location can be conducted through allocation of microdepressions on the watershed surface. The microdepressions at the same time, can be observed in very high resolution satellite imagery (differences in the plowed soil humidification can be used as an interpretation indicator) when enlarged scale investigation is provided in the studied area.

The computational equations developed for seven soil runoff zones made it possible to compile a gridded map of the soil runoff intensity. The results of the soil loss estimations according to the methodology proposed in our study have to be confirmed by the soil-morphological method in the future. Extra soil sampling in the delineated zones will confirm (or refute) the expediency of such a detailed zoning of the arable slope surface. A map of the erosional soil loss intensity makes it possible to assess soil loss with higher accuracy on sloping surfaces that have complex microrelief.

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Satellite image courtesy of DigitalGlobe Foundation.

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