GIS-BASED MODELING OF CAESIUM-137 CONTENT IN SOIL MATERIAL APPLIED TO COMPUTE PLOWED SOIL LOSSES

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ABSTRACT:

The paper describes and discusses possibilities for soil loss estimation in the area of an arable slope using the radiocaesium method, GIS-based analysis, and very high resolution satellite imagery. The interdependences between caesium-137 activity, catchment area value, and the (sign of) profile curvature were estimated using GIS facilities. Interdependencies were estimated for four zones of an agricultural field located in the basin of the Sukhaya Orlitsa River in the Oryol district of the Oryol region (central part of European Russia). The zones were delineated according to differences of surface structure. Special attention was paid to the analysis of the caesium-137 and humus lateral and vertical (in the 0-25 cm arable soil layer) distribution in the area of agricultural field located on the slope of southern exposure. Overplowed soils were detected in one of the delineated zones. Overplowed soils are a type of degraded soils. This soil type was formed under conditions of applying a small amount of fertilizers for the period from 1991 to 2017 in agricultural fields remote from the central estates. In the studied area, the humus content in the arable horizon of plowed gray forest soil was reduced to 4%. The specific activity of caesium-137 does not exceed 140.0 Bq/kg (with its value at the reference plot of 174.7 Bq/kg). The radiocaesium method and estimations of morphometric parameters of topographic relief applied to the computation of soil runoff rate, made it possible to formalize the description of soil losses depending on in-the-relief position of the point, and to compile maps of soil runoff for each of the zones in the field. It was found that the area of overplowed soils is characterized by the largest soil losses (reaching 20 t/ha per year or more). Compiled map can allow to undertake a differentiated approach to the reclamation arrangement of the territory in the analyzed area. If enough fertilizers are applied, the productivity of the overplowed soils can be restored in the future.

1. INTRODUCTION

Intensive soil mineralization occurs, when intensive soil plowing is applied accompanied by a low level of organic fertilizers application, and a low level deposit of post-harvest plant residues in the arable soil horizon. As a result, the level of soil fertility decreases, their agronomic properties deteriorate. Soils appears overplowed and can be classified as degraded soils of varied degrees. The overplowing is a reversible process, on the other hand. After plowing optimizing, the fertility is restored.

Implementation of the precision agriculture principles into the practice of land use requires development of methods for soil runoff estimation according to morphometric parameters of topography of the arable slopes complicated by plowing furrows. Features of the erosion soil loss processes in areas of degraded (overplowed) soils can be pointed as extremely valuable due to high risk of agriculture activities in these areas. Overplowed soils are soils located in watershed areas where intensive plowing is conducted. As the soil exposed to erosion activated by streams formed in the plowing furrows, soil losses are increasing in these areas.

Overplowed soils must be detected accurately on maps of agricultural fields. In Russia, areas of overplowed soils have been formed in fields where insufficient amounts of fertilizers have been applied (Fig. 1) over the past thirty years (after the collapse of the USSR in 1991). These soils are, as a rule, spread out in watershed surfaces, close to roads. Convenient access and relatively flat topography contribute to the intensive annual plowing. Consequently plowed soils are formed (Borisov, 2008; Markelov, 2004; Marusova, 2005; Tarazanova, 2002).

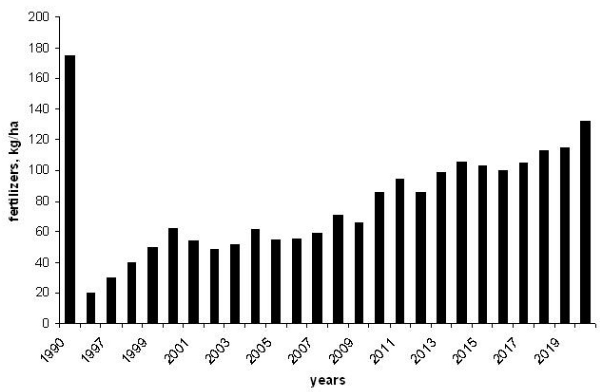

Figure 1. Application of mineral fertilizers to agricultural fields of the Orel region.

From Figure 1 it can be seen that, since 1991, the application of fertilizers to the fields of the Orel region has been insufficient. Only in 2017, the amount of fertilizers applied reached 110 kg/ha (normal value). It can be argued that the decrease in the

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humus content in the arable soils of agricultural fields should have decreased by 15-40 % of initial humus content(Borisov, 2008; Tarazanova, 2002).

Basis of our study was formed by in situ data collected in 2014-2021 at experimental plot of an arable slope in the basin of the Suhaya Orlitsa River (Orlovsky district of the Oryol region, Russia). A zone of overplowed soils was allocated here at watershed, in peripheral area of the arable field 150 m away from the agricultural machinery road.

Analysis of the humus content in soils in the experimental area located on the slope of southern exposure in the basin of the Sukhaya Orlitsa River (Fig. 2) showed that the humus content in the studied area located along the agricultural machinery road (Fig. 3) reduced to 4%. In other areas (outside of arable soils area), the humus content in the arable horizon of 0-25 cm exceeds 4.6–5.0% (Fig. 5). So the humus content is reduced by 13-20%. Reduced value of mobile phosphorus was also found (3-8 mg/100 g). This is 20-50% lower than the average for a field outside of the overplowed soils area (9-21 mg/100g). The specific activity of caesium-137 (which is a marker of the soil washout degree) was also reduced to less than 140-150 Bq/kg (Fig. 4).

Figure 2. Experimental area in the basin of the Sukhaya Orlitsa River (Oryol region). Satellite image courtesy of Google Earth.

Figure 3. A dry streambed on a plowed field with winter crops (photo made on September 05, 2014).

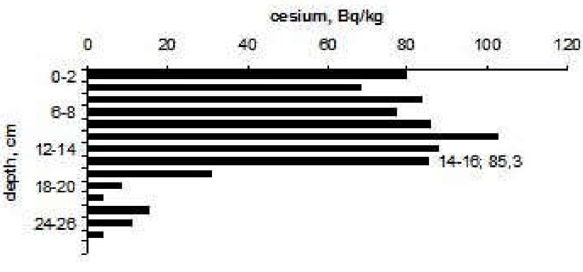

Figure 4. In depth distribution diagram of caesium-137 in the zone of overplowed soils.

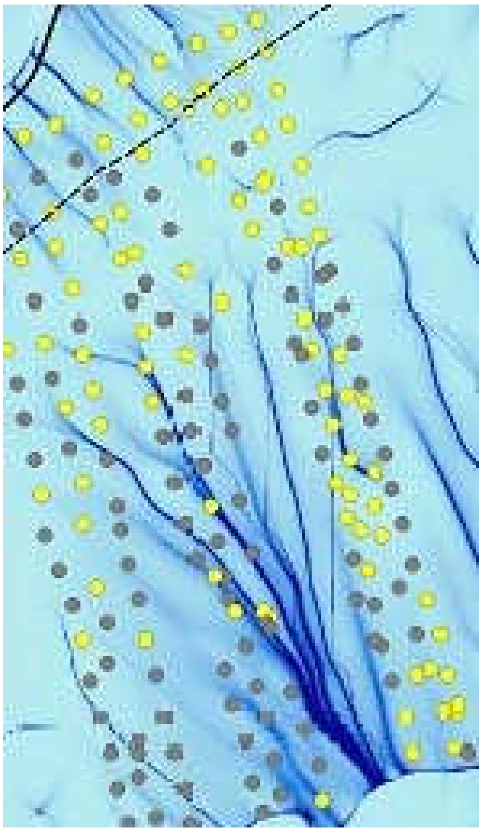

Figure 5. Humus content at soil sampling points compared to the catchment area map (fragment). Grey markers – above 4% humus content, yellow markers – bellow 4% humus content.

2. DATA AND METHODS

In situ data for this study were collected in 2014-2021 on a southern exposure slope located in the experimental area. A zone of overplowed soils at the watershed of the slope was discovered in 2016.

When conducting a total station survey on a sloping section of studied area, we found that the humus content in the arable layer does not exceed 4% (4.6-5 % is an average humus content in gray forest soil in the rest of the field). Figure 4 shows the results of humus content measurements in the arable horizon of 0-25 cm. Yellow markers indicate places of low humus values at the sampling plots.

The radiocaesium method can be recognized as one of the most accessible and effective methods allowing to study the processes of soil runoff and accumulation at slope surfaces (Walling et al., 1999; Walling et al., 2013; Panidi et al., 2016; Trofietz et al., 2019; Trofimetz et al., 2020).We applied the radiocaesium method to elaborate computational models we use for soil runoff estimation. To implement this method we organized layer-by-layer soil sampling in the thalwegs of dry streambeds found in the studied area in the summer-autumn of 2014.

Gamma-spectrometric analysis of soil samples was carried out at the Orlovsky Center for Chemicalization and Agricultural Radiology. Analysis results were used to elaborate computational models of interdependences between caesium-137 radioactivity and morphometric parameters. It was possible to select the most informative indicators from a set of morphometric parameters that would identify the specific radioactivity of caesium-137. These are the catchment area (Costa-Cabral, Burges, 1994) and the sign of profile curvature (Evans, 1972). As a result, the dependence of the caesium-137 specific radioactivity on catchment area values was estimated in regular nodes for the zone of overplowed soil.

3. RESULTS AND DISCUSSION

Analysis of the soil samples showed that soil material of varying washout degree is presented in the streambeds located in area of degraded soil. Gamma-spectrometric analysis and the GIS-based modeling of caesium-137 specific activity spatial distribution in the area allowed us to detect that the caesium-137 activity in the arable horizon of the thalwegs varies from 60.6 to 120.5 Bq/kg (while background radioactivity is 172 Bq/kg). These conclusions were used as the basis for computational models of dependences between caesium-137 activity and morphometric indicators of topography relief.

Additionally, the results of the analysis allowed us to conclude that the soils at the edge of the agricultural field, near the road (zone 3 in Figure 6) are characterized by reduced values of caesium-137 activity. This indicates that the soils in the zone are washed in varying degrees. Figure 4 shows that the activity of caesium-137 in the overplowed soils does not exceed 105 Bq/kg (with the reference value of caesium-137 activity – 174.7 Bq/kg). This conclusion allowed us to clarify the location of the overplowed soil zone.

The boundary was delineated according to the lowest (no more than 140 Bq/kg) values of caesium-137 activity (Fig. 6). The identification of four zones characterized by differences in erosion processes intensity allowed us to develop computational models able to describe dependences of the caesium-137 activity on the catchment area value and the sign of the profile curvature. Dependencies for zones 1-3, were elaborated at previous study stages. These dependences were used finally to compile a map of the soil runoff intensity in the experimental area.

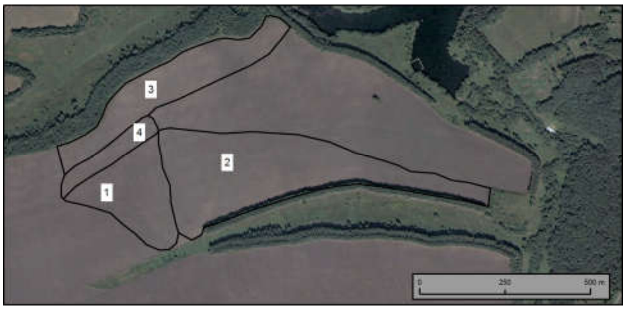

Figure 6. The boundaries of delineated zones sites that differ in the nature of caesium-137 activity dependence on the catchment area. Satellite image courtesy of DigitalGlobe Foundation.

We selected the most "informative" indicators from a set of morphometric indicators of topography relief, which would best identify the specific activity of caesium-137. These are the catchment area (Costa-Cabral, Burges, 1994) and the sign of profile curvature (Evans, 1972). As a result, the dependence of the specific activity of caesium-137 on the catchment area was obtained for the zone of overplowed soils (Fig. 7). The dependence is directly proportional.

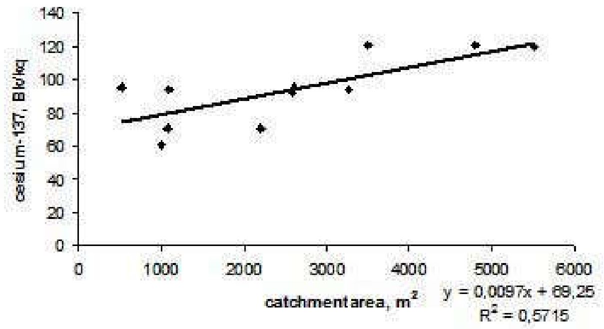

Figure 7. Dependence of the caesium-137 specific activity on catchment area value in zone 3 (overplowed soils in watershed area).

This dependence can be explained by that the studied area is relatively small (the length of the overplowed soil area is not more than 150 meters). As the slope do not exceed a 1.5° here, it does not allow the streams to gain enough energy. Therefore, as we move away from the watershed (where greatest soil degradation occurs due to deep plowing) to the edge of the field, the catchment area values increase insignificantly (from the first hundreds of square meters to 6000 sq. m).

In conditions of shallow bottoms of streams, the soil is more likely to melt from the slope than flushed in the stream thalwegs. Therefore, the activity of caesium-137 increases with an increase in the catchment area (polluted soil is floating off the streambed sides and accumulating in the thalwegs of streams).

The humus content in the arable horizon at block elevations (or in the areas of inter-basin watersheds) in studied area is reduced to less than 4 % (despite the fact that the normal humus content in gray forest soils of the region, as already mentioned, is more than 4%). This fact was confirmed during an experimental studies, while it confirms the fact that the soil contaminated with radiocaesium accumulates in the thalwegs of micro-depressions. In the thalwegs of micro-depressions (in the zone of overplowed soils – zone 3), where the soil is "melting" and accumulated, the humus content increases to 6 %.

The need to clarify the boundaries of zones with different conditions of soil losses formation (due to erosion) required the development of another equation model. On the watershed surface not complicated with micro-depressions network (zone 4), soil flushing is reduced sharply. This zone (the boundaries are limited by the watershed boundaries and the boundary of the overplowed soils zone) was studied to elaborate separated computational model (equation 4 in Table 1). The dependence is presented in Figure 8.

Previously, we elaborated equations for the caesium-137 activity estimation in zones 1-3. Elaboration of the equation for zone 4 allowed us to build a more consistent model of the soil runoff intensity for the experimental area (Fig. 9). This model (set of models) allows to ensure automated map compilation to visualize the intensity of soil runoff. The map compiled for the studied area (Fig. 9) shows that the soil runoff can exceed 20t/ha per year in studied area. The lowest values of soil losses are on the watershed surface and in accumulation zones (where the profile curvature values are negative).

Zone №	Equation	Catch-ment area	Slope exposure	Runoff regime	Profile curvature sign
1	У=-0.0004X +146.00	≤50000	South	Runoff	+
1.1	У=-0.0004X +192,99	≤50000	South	Accum.	-
2	У=-0.0022X +152.96	≤23000	South	Runoff	+
2.1	У=-0.0021X +184.15	≤23000	South	Accum.	-
3	У= 0.0097X + 69.25	≤6000	South	Runoff	+
4	У= -0.0511X +188.74	145-1590	South	Runoff	+

Table 1. Equations for caesium-137 specific activity (Y) estimation using catchment area values (X) in zones 1-4.

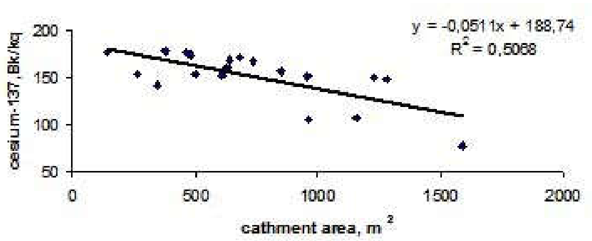

Figure 8. Dependence of the caesium-137 specific activity on catchment area value in zone 4.

Figure 9. A map of the runoff/accumulation intensity, estimations based upon the dependences of the caesium-137 activity on the catchment area and the sign of the profile curvature. Satellite image courtesy of DigitalGlobe Foundation.

4. CONCLUSIONS

In the experimental area located in the basin of the Sukhaya Orlitsa River (Oryol region) on the slope of the southern exposure, four zones were delineated that differ in the conditions of soil formation and in soil washout degree. The soil material sampling exposed to gamma-spectrometric and agrochemical analyses allowed elaborate computational dependences of the Chernobyl origin caesium–137 activity on morphometric indicators of topography relief for each of the four zones delineated in the studied area.

The GNSS positioning for sampling plots and the GIS-based mapping of in situ measured soil characteristics and estimated morphometric topography relief indicators were used in the study.

The catchment area and profile curvature were used as morphometric indicators of topography relief. The developed equations and estimation of the soil runoff intensity provided for each of the four zoned allowed us to compile a detailed map of the soil runoff/accumulation intensity on a 1:10000 scale.

As a result of the study, the applicability of the radiocaesium method in combination with agrochemical analysis and GIS-based analysis is shown for estimation of the runoff (accumulation) of soil material on arable slopes. The study was conducted on the example of arable surface with complex topography relief structure. We recommend to consider zones of overplowed soils in agricultural fields as the characteristic model areas, where special conditions for the course of erosion processes.

Estimation of the possibility to apply the obtained dependence to the caesium-137 radioactivity computation in stream thalwegs formed in plowing furrows (as an indicator of the soil runoff degree) showed that it can be quite successfully applied at the preliminary assessment stage when studying soil losses in areas of degraded (overplowed) soils.

Testing on an independent data showed that at a range of 60.6-120.5 Bq/kg of the caesium-137 specific radioactivity in the area of degraded soil, 82% of the control samples were within a 20% error.

The use of detailed maps equal to developed in the course of the study will allow to take a differentiated approach to carrying out reclamation on soils affected by erosion (including in areas of overplowed soils). In future it can help to reduce the economic costs of soil productivity restoring in agricultural fields of the Upper Oka River basin

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Satellite imagery courtesy of DigitalGlobe Foundation.

REFERENCES

Borisov, B.A., 2008: Easily decomposable organic matter of virgin and arable soils of the European part of Russia zonal range. Dissertation abstract of the doctor of biological sciences. Moscow, 43 p. (In Russian)

Costa-Cabral, M.C., Burges, S.J., 1994: Digital Elevation Model Networks (DEMON): a model of flow over hillslopes for computation of contributing and dispersal areas. *Water Resources Research*, 30(6), 1681-1692. doi:10.1029/93WR03512

Evans, L.S., 1972: General geomorfometry, derivatives of altitude, and descriptive statistics. In: Chorley, R.J.b(Ed.), Spatial Analysis in Geomorfology. Methuen & Co., Ltd., London, Chap. 2, 17-90.

Markelov, M.V., 2004: Modern erosion-accumulative processes in the upper segments of hydrographic network of the forest and forest-steppe zones. Dissertation abstract of the candidate of geographical sciences, Moscow, 22 p. (In Russian)

Marusova, E.A., 2005: The influence of natural and anthropogenic factors onto the properties of arable gray forest soils of the southern Moscow region. Dissertation abstract of the candidate of biological sciences, Moscow, 25 p. (In Russian)

Panidi, E., Trofimetz, L., Sokolova, J., 2016: Application of phyto-indication and radiocesium indicative methods for microrelief mapping. *IOP Conference Series: Earth and Environmental Science*, 34(116), 012024. doi:10.1088/1755-1315/34/1/012024

Tarazanova, T.V., 2002: Tillage degree diagnostics of soils of the European part of Russia zonal range. Dissertation abstract of the candidate of biological sciences, Moscow, 148 p. (In Russian)

Trofietz, L.N., Panidi, E.A., Chaadaeva, N.N., Sankova, E.A., Ivaneha, T.L., Petelko, A.I., 2019: Estimation of the quantity of soil loss in the thalwegs of the streams formed by heavy rainfalls in the breakup furrows at arable slopes: Application of satellite imagery, GIS and radiocesium method. *InterCarto, InterGIS Proceedings*, 25(2), 217-231. doi:10.35595/2414-9179-2019-2-25-217-231 (In Russian)

Trofimetz, L.N., Panidi, E.A., Chaadaeva, N.N., Sankova, E.A., Ivaneha, T.L., Tyapkina, A.P., Petelko, A.I., Alexandrova, A.P., Ladnova, G.G., 2020: Determining the reference value of Cesium-137 specific activity on arable slopes in the periglacial area of the Upper Oka basin: application of satellite images, GIS and soil agrochemical indicators. *InterCarto, InterGIS Proceedings*, 26(3), 170-183. doi:10.35595/2414-9179-2020-3-26-170-183 (In Russian)

Walling, D.E., Golosov, V., Olley, 2013: Introduction to special issue Tracer application in sediment research. *Hydrological Processes*. 27(6), 775-780.

Walling, D.E., He, Q., 1999: Improved models for estimating soil erosion rates from Caesium-137 measurements. *J. of Environ. Quality*, 28(2), 611-622.