Mapping and forecasting of changes of eroded soils (Central-chernozem region of Russia)

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Abstract. The paper presents assessment of the current state and risk of soil degradation of arable land (area ~800 sq. km.) from erosion. The rates of soil erosion were calculated by the WATEM/SEDEM. The obtained rates of soil erosion were converted into erosion losses of the soil profile and compared with the current thickness of the humus horizons (according to field survey data). The calculated and actual (according to the field survey) soil losses correspond to each other. The rate of soil erosion in the southern section is almost twice higher than in the northern section, however, the difference in the area of eroded soils is 4.4 times higher. The forecast was calculated for each pixel with respect to the current thickness of the humus horizons. With the stable rate of erosion in the next 50 years, the area of eroded soils will almost double on the studied territory, and in 200 years will grow almost 3 times relative to the current state. After 200 years of plowing without soil protection measures, the share of eroded soils in the northern section will only reach the current level of soil degradation in the southern section, while the share of eroded soils on south section will reach almost 35%. These results clearly demonstrate that the areas of priority application of soil conservation measures should be determined not by the rate of erosion, but by the rate of degradation of the soil cover from erosion.

1. Introduction

In recent decades, many countries have focused on ecological farming aimed at preserving the environment. One of the most important components of the environment is soil, which is highly transformed by agricultural use. The gravest threat among all soil degradation processes is soil erosion (Montanarella et al., 2016). In Russia alone, more than 500 million tons of soil matter is washed out from arable slopes annually (Akimov et al., 2009).

Scientific and practical research, as a rule, is aimed at quantifying the rate of erosion, while much less attention is paid to the state of soils and the forecast of their degradation in the future. For example, J. Poesen (2018) identified the following needs for more research attention: (1) improved understanding of both natural and anthropogenic soil erosion processes; (2) scaling up soil erosion processes and rates in space and time; (3) innovative techniques and strategies to reduce erosion rates. Of course, these goals are significant. However it is important to consider that the average rates of soil erosion calculated for entire slopes and catchments do not reflect the real situation of soil degradation, because different scenarios of soil degradation are possible at the same average rates of soil erosion on slopes with different topography, land use, soil properties in their original and current state, etc.

At present, it becomes obvious that it is impossible to radically change the situation by
completely suppressing soil erosion processes. Establishment of soil protection measures is extremely expensive and economically not viable in a modern market economy. The main way out of this situation is to identify the territories most susceptible to soil degradation from erosion, forecast the intensity of soil degradation in the future, and protect lands with the most negative scenarios of soil degradation.

The purpose of this work was: 1) assessment of the intensity of erosion processes in the past (based on the WATEM / SEDEM model); 2) validation of calculation data with the actual degree of soil degradation (obtained from field survey data) and mapping of soil areas with different degrees of erosion; 3) predictive assessment of soil degradation in the future.

2. Materials and methods

The study area is located in the southeastern part of the Central Russian Upland in Belgorod region, Prohorovskii district. The area of the Prohorovskii district is ~1 350 sq. km, and the area of the arable land is ~800 sq. km. The soil cover of arable land is mainly represented by Haplic Chernozems (about 55% of the arable land area) and Luvic Chernozems, Luvic Chernic Phaeozems (about 40% of the arable land area). The relief is represented by a slightly wavy upland plain with absolute heights from 128 to 269 m (Fig. 1A).

Soil erosion rates were calculated by the WATEM/SEDEM v. 2004 model (Van Oost et al., 2000; Van Rompay et al., 2001). A detailed description of the analysis of input parameters is presented in (Zhidkin et al., 2020). This paper presents the results of mapping the soil cover of arable land in the Prokhorovsky region on the basis of the traditional (visua- expert) method and using digital modeling of soil erosion. The values of the input parameters are presented below: R = 270-320 MJ·mm·ha·h·yr\(^{-1}\); K = 0.035 t·ha·ha\(^{-1}\)·MJ\(^{-1}\)·mm\(^{-1}\); C = 0.4; the digital elevation model was compiled with a cell size of 20 meters based on a topographic map of high resolution. The detail of this digital model is extremely high considering the area of the study area - 800 sq. km.

Field studies were carried out by the state «Belgorod agro-ecological service». Soil properties were analyzed at 639 sampling points by excavating soil pits. The interpolation of the thickness of the humus horizons was carried out by the method of multiple linear regression. The proportion of eroded soils was calculated as the proportion of the number of pixels with the thickness of the humus horizon <40 cm of the total number of pixels.

Predictive assessments of soil degradation were carried out as follows. A table was compiled for all pixels (about 2.2 million pixels), with data on the current thickness of humus horizons and the rate of soil erosion. For each time period (with a step of 25 years), erosion losses and the residual thickness of the humus horizon were calculated for each pixel. Further, for each time period, the proportion of pixels with eroded soils (the thickness of humus horizons in which is <40 cm) was calculated.

The study area was divided into two parts - northern and southern (Fig. 1). The border is laid along the watershed. The northern section belongs to the drainage basin of the Seim River (a tributary of the Dnieper), and the southern section of the study area belongs to the drainage basin of the Northern Donets (a tributary of the Don River). The northern part is characterized by less rugged relief, in contrast to the southern part. The slopes of the northern section of the section have a predominantly northern exposure, and the southern section - the southern exposure. The arable land area of the northern section was 50.2%, and the southern section 40.8% of the total arable land in the Prokhorovsky district of the Belgorod region.

3. Results and Discussion

Among the studied 639 soil pits: 235 were non-eroded (soils of watershed areas), 230 - weakly eroded (the thickness of the humus horizon is <20 cm less than on the watershed), 157 - medium eroded (the thickness of the humus horizon is 20-40 cm less than on the watershed) and 4 - on strongly eroded (the thickness of the horizon is more than 40 cm less than on the watershed).
The average rate of soil erosion, calculated for the entire arable land, is 4.2 tons ha\(^{-1}\) per year. On some slopes, the rate of erosion reaches significantly higher values, up to several tens of tons ha\(^{-1}\) per year. The northern and southern sections differ significantly. The rate of soil erosion in the northern section is 2.9 tons ha\(^{-1}\) per year, and in the southern it is almost twice higher (5.6 tons ha\(^{-1}\) per year) (Fig. 1b). Differences in the intensity of soil erosion are primarily due to the features of the relief. The relief in the southern section is much more dissected and characterized by higher slopes than in the northern section. The highest rates of erosion are observed on the slopes adjacent to large gullies in the central part of the southern section (Fig. 1b).

Despite such significant differences in the rates of erosion between northern and southern sections, the differences in the thickness of the humus horizons do not appear so contrasting at first glance. The thickness of the humus horizons in the northern section is 56.9 cm, in the southern section it is 51.9 cm at present.

The duration of plowing of this territory varies from 170 to 310 years. Plowing in the study area took place primarily in areas with low rates of soil erosion. The calculated rates of soil erosion in areas with a long plowing period (~4.4 tons ha\(^{-1}\) per year) were almost 2 times lower than in areas with a short plowing period (~7.5 tons ha\(^{-1}\) per year). As a result, the differences in the degree of soil cover erosion between plots with different plowing times are not expressed in contrast. To simplify the calculation, the duration of plowing was averaged to 200 years.

The above rates of soil erosion correspond to the following erosional losses of the humus horizon over 200 years: ~4.3 cm (residual thickness ~55.6 cm) in the northern section and ~8.9 cm in the southern section (residual thickness ~51.1 cm). The rates of soil erosion are roughly calculated. A significant detailing of changes in the rate of erosion is possible based on an analysis of changes in factors over the past 200 years, in particular: climate, composition of crops, etc. Nevertheless, the thickness of the humus horizons on average correspond to the calculated erosion losses, even taking into account not high detail of changes in the rate of soil erosion over time.

According to the field survey, the share of eroded soils in the study area is 7.3% (6245 ha) on average. There is very strong difference in this indicator between the northern and southern sections. The share of eroded soils in the northern section is only 2.7%, while in the southern section it is almost 4.5 times higher - 11.9%; the area of eroded soils is 1169 ha in the northern section, in the southern
section it is 5076 ha (Fig. 2).

It is important to note that the differences in the rates of soil erosion between the northern and southern areas are less than 2 times, while the area of eroded soils and their share of the total arable land area differ by 4.4 times currently. The changes of the area of eroded soils in time is determined not only by the rate of erosion, but also by the spatial features of erosion processes, which are largely determined by the relief. In the case of straight slopes, the rate of erosion downslope changes linearly, as a consequence the area of eroded soils will also change linearly with time for the same intensity of erosion. However, each slope has its own morphology and spatial distribution of the intensity of erosion. Therefore, the curve of the change in the area of eroded soils in time will be smooth (close to linear) on some slopes and sharply bend on other slopes. Sharp changes are possible within territories, a significant part of which has the similar rate of erosion, and, as a consequence, the same rate of soil degradation over a wide area. Achievement of the category of eroded soils will occur simultaneously and abruptly for the entire area with the same rates of erosion.

Fig. 2 shows the calculated changes in the share of eroded soils. The calculation was carried out for each pixel (about 2.2 million pixels in total) according to the method described above. The forecast calculation was carried out with respect to the current thickness of the humus horizons, revealed during the field survey. With a stable rate of erosion in the next 50 years, the area of eroded soils will almost double, and in 200 years will grow almost 3 times relative to the current state.

![Figure 2. Current actual and calculated changes in the share (by area) of eroded soils in the previous 200 years and the next 200 years of plowing on arable land in the Prokhorovsky district.](image)

Differences in the share of eroded soils between the northern and southern areas were clearly manifested. The impact of erosion on soil degradation in the northern section is much lower than in the southern section. It is important to note that with a stable rate of erosion, the soil cover of the northern section will reach the current degree of degradation of the southern section only after 200 years of its active use in agriculture. These results indicate the high risks of soil degradation and the need for soil protection measures in the southern part of the Prokhorovsky region. At the same time, in the northern part of the Prokhorovsky region, the problem of soil erosion is generally not so threatening. Wherein the rates of soil erosion between the northern and southern areas do not differ so much (by 2.7 tons ha$^{-1}$ per year).

The graphs of changes in the proportion of eroded soils are nonlinear, have different degrees of curvature in different periods. Both curves are best described by a third-order polynomial with a value of the approximation confidence $R^2 > 0.99$. In the initial period, there is an exponential increase in the


proportion of eroded soils, and then a gradual slowdown in growth over time. The southern section is at the “bending” stage of the curve; in the future, the growth will be relatively stable (almost linear). The northern section is characterized by an exponential growth in the proportion of eroded soils in the coming decades. Interestingly, the differences in the proportion of eroded soils between the northern and southern sites vary at different periods of time. At present, the areas of eroded soils differ maximum - 4.4 times. In the initial period of plowing, the differences were 2-2.5 times; after 200 years, the differences will decrease to 2-2.5 times.

4. Conclusion
The model WATEM/SEDEM showed a fairly high correspondence between the calculated volumes of soil erosion and actual erosion losses (obtained on the basis of field survey of soils) for the entire plowing period. The rate of soil erosion and the intensity of soil cover degradation do not fully correlate with each other. In particular, in the northern and southern parts of the study area, the rates of soil erosion differ 2 times, while the areas of eroded soils differ almost 4.5 times currently. Even in the case of relatively stable rates of erosion in the future, the areas of eroded soils will not increase linearly. Forecast assessments of soil degradation revealed significantly different scenarios for the growth of eroded soils in the northern and southern areas with a difference in erosion rates of only 2.7 tons ha\(^{-1}\) per year. In the northern part of the Prokhorovskiy region, the problem of soil erosion is generally not so threatening. The rate of soil degradation is relatively low; if it is plowed up for another 200 years without carrying out soil protection measures, it will only reach the current degree of degradation of the southern section (the share of eroded soils is \(\sim 12\%\)). While the southern site needs soil protection measures, since without them the share of eroded soils will increase by 5-6% every 50 years and in 200 years will reach almost 35%. It is necessary to take into account the scenarios of soil degradation (and not just the rate of erosion) when developing soil protection measures.

5. Acknowledgments
The work was done with the financial support of the Ministry of Science and Education of the Russian Federation and experimental developments in the framework of the implementation of the Federal Targeted Program “Research and Development in Priority Areas of the Scientific and Technological Complex of Russia for 2014-2020”. (Agreement No. 075-15-2019-1689 of 06.12.2019) with a unique project identifier RFMEFI60419X0222.

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