Variation of Soil Erosion Estimates Based on Different Maps of Cropland in Belgorod Oblast, Russia

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Abstract—Current medium- and small-scale estimates of soil erosion in Russia are very few. At the same time, a favorable situation has now developed for assessing the rates and volumes of soil erosion losses. Erosion models adapted to available digital elevation models, various farmland maps, and climate databases are now available to researchers. We have estimated the rates and volumes of soil erosion with the use of different maps of cropland: world cover from the European Space Agency (ESA WC), global land cover and land use from the University of Maryland (GLCLU), the official unified federal information system of agricultural land (UFIS AL) from the Ministry of Agriculture of the Russian Federation, and the original conventionally reference land cover map of Alekseevskii district of Belgorod oblast. It has been found that the UFIS AL map gives cropland areas close to the average from first three maps. Public access maps (ESA WC and GLCLU) give maximum and minimum estimates of cropland, respectively. A comparison with the conventionally reference large-scale map shows that the accuracy of the UFIS AL does not exceed 90%; the accuracy of ESA WC and GLCLU maps is 84 and 83%, respectively. The total area of cropland in Belgorod oblast varies slightly (from 1445 to 1586 thousand hectares), which is favorable for erosion modeling. Deviations from the average rates of soil erosion calculated using different maps of cropland in the region as a whole are up to 7%; for some districts, they reach 27%. Thus, current estimates of soil erosion at the regional level can be carried out with an error of at least 10−15% only as a result of the uncertainty in mapping the boundaries of cropland. For Russia as a whole, data on the area of cropland vary significantly: from 80 to 132 million hectares. Consequently, the use of existing maps of cropland can lead to significant uncertainties in soil erosion estimates averaged at the level of the subjects of the Russian Federation and large regions.

Keywords: WaTEM/SEDEM, UFIS AL, ESA World Cover, Global Land Cover and Land Use, retrospective monitoring of soil and land cover, chernozem, soil degradation

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INTRODUCTION

Soil erosion causes significant damage to the environment. Erosional losses of soil from croplands in Russia amount to more than 500 million tons per year [15]. A significant part of soil erosion estimates were obtained in the 1980s as a result of generalizations of the results of soil erosion surveys. Modern assessments of soil erosion at the regional and national levels are carried out mainly on the basis of erosion models [13, 23, 35, 38, 41, 46] due to the lack of other available methods for studying soil erosion rates at medium and small scales. It is important to note that over the past decades, erosion model algorithms have been significantly improved; various models have been verified, including verification for the territory of Russia [41, 53, 54]. Active work is underway around the world to improve approaches and detail quantitative assessments of soil erosion factors (input modeling parameters): erosion potential of terrain and precipitation, soil erodibility, etc.

One of the most important factors in the development of erosional−depositional processes is the structure of land use. Under natural vegetation, the rate of soil erosion is many times lower than on croplands [49]. Changes in the configuration of plowed areas and the position of the cropland boundary in the relief, as a rule, significantly affect soil erosion. Even a slight change in the configuration of field boundaries and a reduction in the area of cropland within a small catchment by only 5% has led to a decrease in erosion losses from the cropland of the catchment by a third [54]. Thus, the accuracy of land use boundaries is important for soil erosion estimates. Insufficiently accurate accounting of the boundaries of cropland in the lower, most erodible parts of the slopes can lead to a significant distortion of estimates of the rate and volume of soil erosion. Unfortunately, this factor is rarely ana-

lyzed in studies. As a rule, one source of information about the boundaries of cropland is used, the accuracy of which is often not specified. Works on assessing the influence of detailed information about land use boundaries on quantitative estimates of the rate and volume of soil loss are virtually absent. In recent years, there has been an active development of approaches to mapping the boundaries of agricultural fields, including those based on remote sensing (RS) data.

Estimates of the area of cropland in Russia vary enormously. According to statistical reference books of the state federal service [1, 9, 33] they range from 79.9 to 134 million hectares. According to [9], from 1990 to 2020, sown areas in Russia decreased from 117 to 79.9 million hectares. Unplowed lands should be mapped as fallow land; however, according to the Federal Service for Registration, Cadaster, and Cartography, the area of fallow land in Russia in 1998–2020 was only about 3.9–4.9 million hectares [33].

The lack of a single accurate large-scale cartographic system for the cropland in Russia leads to the existence of many sources that differ in creation methods, spatial resolution, and other indicators [17].

In addition to large-scale estimates, there are regional estimates of the area of cropland and its dynamics [6–8, 42]. Regional estimates of arable area are based on modeling and statistics. There are different opinions regarding the correctness and accuracy of regional statistical estimates of cropland area [30]. In the context of our study, it is important that regional statistical data cannot be taken into account in erosion modeling. Cropland boundaries can be loaded into the model in the form of large-scale maps. The work evaluates large-scale maps of actually plowed cropland (cultivated cropland). The most detailed of the cropland maps have a scale larger than 1 : 10000.

Analogous problems appear not only in soil erosion modeling. For example, modeling cropland carbon content [39, 45, 51] under a changing climate requires a similar set of input parameters. Before the widescale application of RS data, the following materials were used to solve them: land use maps [14], soil maps [25], maps of agroclimatic zoning [31], climate databases [44], agrophysical indicators of soil cover [34], etc. Currently, the availability of data for modeling has changed.

Relatively accessible materials reflecting the distribution of cropland in Russia are as follows: the unified federal information system of agricultural land (UFIS AL) [10], the public cadastral map [33], USGS agricultural land maps [40], a map of unused agricultural land potentially suitable for forest growing [16], land cover (land use) model ESA World Cover 2020 (ESA WC) [52], Global Land Cover and Land Use (GLCLU) model [43], TerraNorte model [2], and Copernicus Global Land Service model [37].

The following maps of agricultural lands have a relatively low spatial resolution: USGS maps [40], 500 m;

TerraNorte map [2], 230–250 m; Copernicus Global Land Service maps [37], 100 m. On the public cadastral map [33], polygon attributes include not the actual type of agricultural land, but the type of permitted use, which makes it difficult to clearly identify actually cultivated (arable) land. The map of unused agricultural lands potentially suitable for forest growing [16] has some gaps, including those in Belgorod oblast.

Thus, three sources are best suited for assessing soil erosion: UFIS AL [10], ESA WC [52], GLCLU [43]. All of them are characterized by the absence of gaps, have high spatial resolution (at least 30 m), clearly identifiable cropland, as well as documented and reproducible sequences of actions to obtain them.

In addition to these sources, there are several others, for example, Demetra GIS [24] and field schemes of the Agrochemical Service of the Ministry of Agriculture of Russia [5], which are extremely difficult to access, and, therefore, their use is difficult.

The purpose of this study is to compare quantitative estimates of the rate of soil erosion and the volume of erosion losses obtained from erosion modeling with the use of different sources of information on the actual configuration and area of cropland on the scale of administrative regions (oblasts) and districts.

Belgorod oblast was chosen as the object for this study, because it is characterized by a high proportion of cropland, generally high rates of soil erosion [12, 38, 46] and, at the same time, a significant diversity of particular manifestations of erosional and depositional processes in different areas.

OBJECTS AND METHODS

Belgorod oblast has an area of 27.1 thousand km^2. This is one of the most agriculturally developed regions of Russia: cropland occupies about 55–60% of the total area. Belgorod oblast ranks 12th among the regions of the Russian Federation in terms of gross grain harvest (≈3 million tons in 2021), despite the fact that it ranks only 67th in terms of area. About 80% of the entire area of Belgorod oblast and about 90% of its arable area is occupied by chernozems [38].

The development of these lands began in the 16th century. Until the end of the 17th century, the area of cultivated land remained small. At the turn of the 17th and 18th centuries, with the cessation of regular raids by nomads, the southern part of Belgorod oblast was populated, and its active agricultural development started. This intensified the development of erosion processes [32]. According to a large-scale soil erosion survey in the 1980s, the share of eroded cropland was 49.9%. The area of eroded territories continued to increase by 6% by 2010 [19]. The eroded soils of the Belgorod region lost about 130 million tons of humus; as a result, the annual shortage of products in terms of grain amounted to about 1.22 million tons [22].

The development of erosion processes in Belgorod oblast is facilitated by a large area of cropland, strongly dissected topography, stormy rainfall, relatively low erosion resistance of soils, as well as a high proportion of row crops in crop rotations.

Quantitative estimates of the current rates of soil erosion in Belgorod oblast vary within a very wide range from 1.3 to 21.5 t/ha per year [12].

In our study, soil erosion was assessed on the basis of the WaTEM/SEDEM model. The erosion potential of the terrain (slope and slope-length (LS) factor) was calculated using SRTM with a resolution of 30 × 30 m and equations [47]. The rainfall intensity factor (R factor) was taken equal to 280 MJ mm/(m^2 h yr) according to [48]. The protective potential of vegetation (the cover-management C factor) was taken equal to 0.40 according to data on the share of crops in crop rotation and the agroerosion index of crops in this zone according to Larionov [18]. The soil erodibility factor K was 35 kg h/(MJ mm) according to [13]. The use of averaged values of R, C, and K factors in erosion modeling makes it possible to assess soil erosion with a high degree of conditionality. However, this approach seems acceptable for the stated goal of our study—a comparative analysis of estimates of the rates and volumes of soil erosion as dependent on the used maps of cropland distribution. In addition, our assessments were carried out on the scale of the entire oblast and its districts. Certainly, a more detailed assessment of soil erosion requires greater detail in the input parameters, as well as verification of model estimates. However, such detailed assessments of soil erosion for the large-scale level of the subjects of the Russian Federation are still rare [11, 38].

Calculations of the rates and volumes of soil erosion losses were carried out with the use of three maps of the boundaries of cropland obtained from different sources: (a) the unified federal information system of agricultural lands (UFIS AL) [10] obtained upon request from the Analytical Center of the Ministry of Agriculture of the Russian Federation; (b) ESA World Cover 2020, which is publicly available on the Internet (https://worldcover2020.esa.int/); and (c) the Global Land Cover and Land Use (GLCLU) model, which is also publicly available on the Internet (https://glad.umd.edu/dataset/global-land-cover-land-use-v1).

To create maps of cropland, both raster maps (ESA WC, GLCLU) and vector maps of agricultural land (UFIS AL) were used. All non-arable land in the study area was removed from the final maps of arable land (cropland).

Algorithm for creating the ESA WS 2020 model consisted of three stages: pre-processing, classification, and map development. At the pre-processing stage, Sentinel-1 synthetic aperture radar images, as well as multispectral, mostly cloudless, Sentinel-2 images with a resolution of about 10 m were chosen. Classification based on the decision tree algorithm with gradient boosting was applied [50]. The resulting land cover model is current for 2020; it is distributed in fragments of 3° × 3° in the geographic coordinate system (WGS 84).

The ESA WC model allows the identification of 11 land cover classes according to the FAO classification. For this study, only information about cropland was used, i.e., ESA WC was converted into the map of cropland boundaries in Belgorod oblast in the form of a raster with a resolution of 30 × 30 m.

Algorithm for creating the GLCLU model is based on the decision tree classification method [36] applied for categorical data and the sum-of-squares regression trees method for continuum data. Input data for these algorithms are derived from 16-day composites of Landsat images with a resolution of 30 m. Two versions of the model have been obtained. First, this is a model that provides more detailed attribute information about the height of the forest stand, the percentage of projective cover for forest areas, as well as the projective cover for herbaceous vegetation. Second, this is the actual land use model with generalized attribute information about woody and herbaceous vegetation, as well as other types of land cover. We used the second version of the model containing 19 classes. For these studies, as in the previous model, only information about cropland was used. GLCLU was also converted into the map of cropland boundaries in Belgorod oblast in the form of a raster with a resolution of 30 × 30 m.

In addition, for reference assessments, the boundaries of the agricultural fields in Alekseevskii district were digitized with high detail using the method of retrospective monitoring of soil and land cover (RMSLC). The map of plowed fields in Alekseevskii district was created on a scale of 1 : 10000 based on thematic interpretation of satellite images (from 1984 to 2022) with a spatial resolution from 0.8 to 30 m using the RMSLC method [3, 26–29]. For internal verification purposes, topographic and cadastral maps of various scales (from 1 : 25000 to 1 : 200000 were used). The maximum accuracy of identification of modern cultivated cropland was achieved through retrospective monitoring of lands and identification of lands that, firstly, were constantly cultivated; secondly, were abandoned (fallowed); and, thirdly, fallow lands recently involved in agricultural use. For Alekseevskii district, the RMSLC map was adopted as the reference map for agricultural lands; it was considered the only map corresponding to the cartographic accuracy of 1 : 10000 survey scale [17].

Hypotheses about the equality of the average values of the calculated rates of soil erosion and volumes of soil erosion losses obtained using different cropland boundaries were tested using the Student's t test. A total of three pairs of samples based on the different maps were compared with one another: ESA WC and GLCLU, UFIS AL and ESA WC, UFIS AL and GLCLU.

Table 1. Cropland areas in Alekseevskii district according to the UFIS AL, ESA WC and GLCLU maps compared to the reference RMSLC map

Map	Area, ha				
	cropland, ha	intersection with the RMSLC map	type I errors	type II errors	combination with the RMSLC map
UFIS AL	94928.95	90429.15	4499.80	5396.64	100325.60
ESA WC	100900.60	90489.61	10410.99	5336.18	106236.78
GLCLU	89700.15	84790.58	4909.56	11035.21	100735.36

The calculation of the maximum absolute deviation from the average was carried out for the following indicators: (a) cropland area, (b) calculated soil erosion rates, and (c) calculated volumes of erosion losses of soils averaged over the districts of Belgorod oblast. Maximum deviations from the average (μ) were calculated using the formula:

$$\mu = \frac{\left|\max\{X_i - \bar{X}\}\right|}{\bar{X}}, \qquad (1)$$

where X_i is the cropland area (ha) obtained from cropland maps UFIS AL, ESA WC, and GLULC; and $\bar{X}$ is the average of the three values of cropland area obtained from these cropland maps.

RESULTS AND DISCUSSION

Comparative analysis of cropland areas. Maps of arable land (cropland) in Alekseevskii district UFIS AL, ESA WC, and GLULC were subjected to pairwise intersection with the reference RMSLC map (Table 1). As a result, the areas of cropland were compared and errors of the first type ("missing the target") and the second type ("false alarm") were assessed. An error of the first type was understood as the absence of cropland on the analyzed maps in places, where it was actually present in 2022 and displayed on the reference RMSLC map. An error of the second type was understood as the presence of cropland on the analyzed maps in places, where it was actually absent in 2022 and, hence, not displayed on the reference RMSLC map.

According to the reference RMSLC map, in 2022, cultivated cropland area in Alekseevskii district comprised 95826 ha out of the total district area of 177680 ha. The UFIS AL map gives cropland area in the district equal to 94929 ha, which is close to the reference value. However, on the UFIS AL map, there are 4500 ha of cropland corresponding to type II error, i.e., shown in places, where there is no cropland according to the reference map. Another 5397 ha of real cropland are missed on the UFIS AL map (type I error). Thus, the total error of cropland representation on the UFIS AL map (missed areas and redundant areas) is about 10% of the real estimate.

According to the ESA WC model, cropland area in Alekseevskii district is 100901 ha. The error of the first

type is 10411 ha, and error of the second type is 5336 ha. In total, the share of erroneously detected cropland area reaches 16%. The GLCLU map gives the cropland area of 89700 ha. The error of the first type is 4910 ha, and the error of the second type is 11035 ha. In total, the share of erroneously detected cropland is 17%.

In addition, we constructed the maps indicating cropland areas shown on (1) all the source maps and (b) at least one of the source maps. That is, we obtained minimum (80429 ha) and maximum (110735 ha) estimates of cropland area in Alekseevskii district according to all the available sources. The ratio between cropland areas upon intersection and combination of the source maps was 0.73.

A comparative analysis of the maps indicates that the ESA WC model tends to overestimate cropland area. In almost all districts of Belgorod oblast (except one), this map gave overestimated cropland areas (Table 1S). In turn, for the GLCLU model, a tendency to underestimate cropland areas was revealed. In most districts of Belgorod oblast, cropland areas on the GLCLU map were minimal.

The total number of cultivated fields was calculated for each of the considered maps. The maximum number of fields (29300 for Belgorod oblast) was identified on the UFIS AL map. This indicates the greatest fragmentation of the areas of cultivated fields on this map. A slightly smaller number of fields (26800) was identified on the ESA WC map. The minimum number of fields (only 11300) was on the GLCLU map. Thus, in the GLCLU model, neighboring fields were artificially combined into single mapping areas, and the fragmentation of cropland areas was almost two times lower than that on the UFIS AL map. On the ESA WC map, neighboring cultivated fields were also artificially united into single mapping areas. A large number of cultivated fields on this map was due to numerous small fields shown on floodplains and in the ravine network. In most cases, these small areas of grassed land were erroneously attributed to cropland on the ESA WC map, as they are not shown as cropland on the other maps (Fig. 1).

For each district of Belgorod oblast, the maximum deviations from the average cropland areas were calculated using formula (1). In general, a tendency was revealed for a greater number of errors in mapping
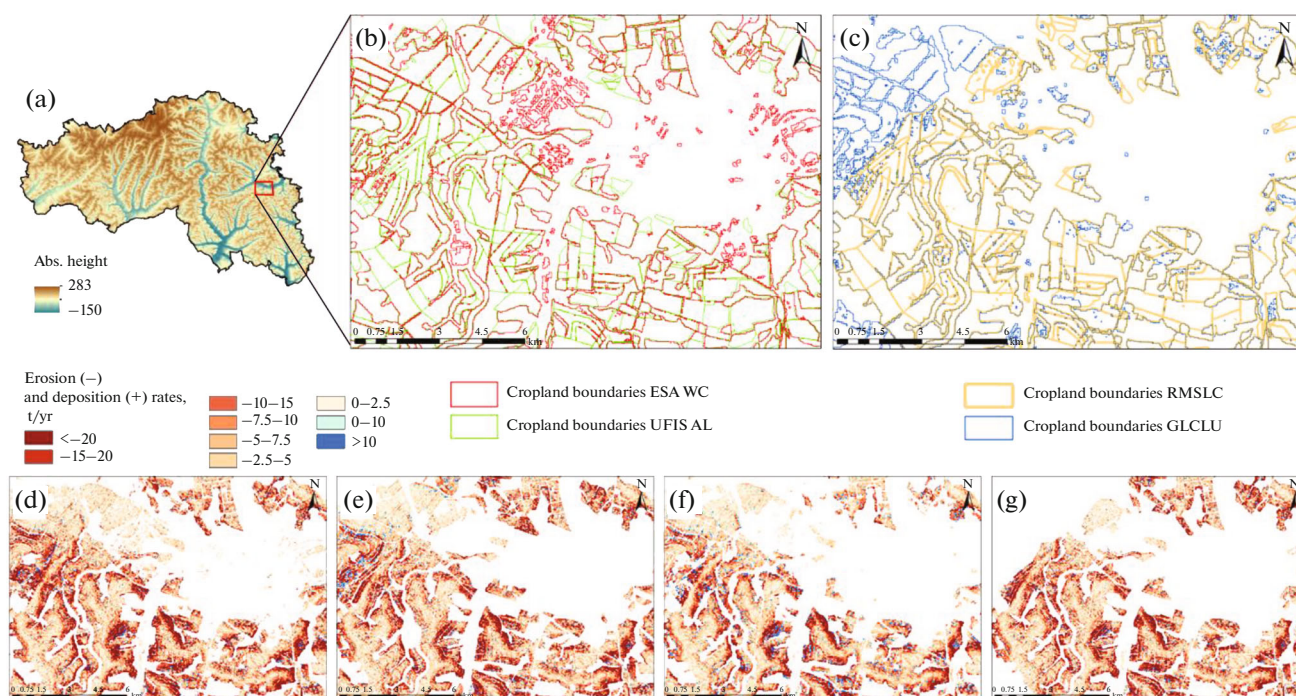
Fig. 1. Location of the mapped key area (a) and maps of (b, c) agricultural field boundaries and estimated rates of erosion-accumulation processes obtained using (d) ESA WC land use models, (e) UFIS AL, (f) GLCLU, and (g) RMPZP.
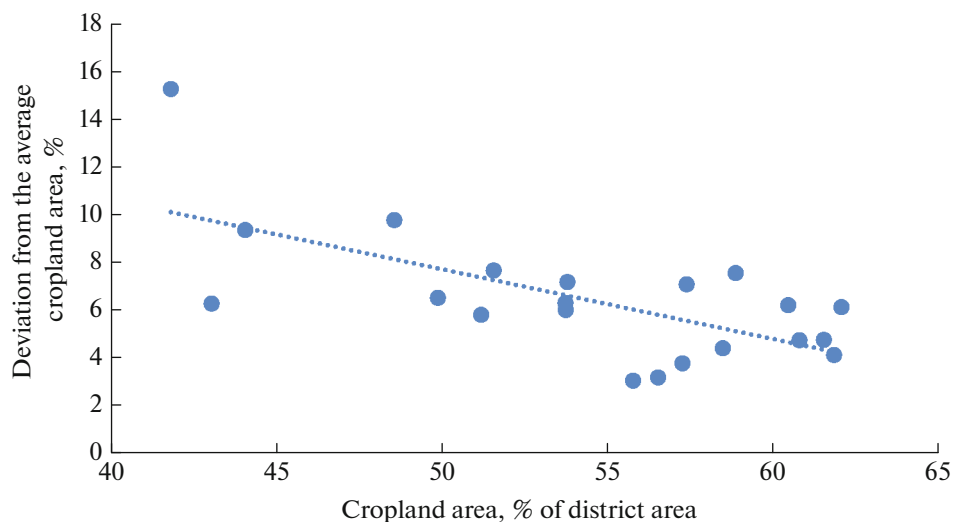

Fig. 2. Graph of the relationship between the deviation from the average cropland area and the share of cropland in the total area of administrative districts of Belgorod oblast.

cropland areas for the territories with a smaller share of cultivated fields (Fig. 2).

The ratio of cropland areas calculated for the entire Belgorod oblast and for Alekseevskii district on each of the maps varies from 15.19 to 15.34, which is close to the ratio of the total areas of Belgorod oblast and Alekseevskii district (15.28). Thus, we can assume that the accuracy of the UFIS AL, ESA WC,

and GLCLU maps for the entire oblast as a whole corresponds to the accuracy of these maps calculated for Alekseevskii district.

For the entire oblast, intersection of the three cropland maps gives the cropland area of 1.22 million ha; the combination of the three cropland maps gives the cropland area of 1.68 million ha. The ratio of the intersection area to the combined area is 0.73, which coin-

cides with a similar ratio calculated for Alekseevskii district.

Thus, a comparative analysis of three land use models made it possible to place them in the following order according to accuracy of displaying cropland estimated as the sum of errors of the first and second types: UFIS AL (10%) < ESA WC (16%) < GLCLU (17%). The total cropland area marked on all the maps differs from the total cropland area marked on at least of the maps by 27%.

Comparative analysis of soil erosion rates. In this work, the rate of soil erosion refers to the rate of removal of soil matter beyond the cropland (net erosion) expressed in t/ha per year. The estimated rate of soil erosion in Alekseevskii district was 5.6 t/ha per year as based on the reference RMSLC model, 5.8 t/ha per year when using the UFIS AL model, 5.9 t/ha per year when using the GLCLU model, and 6.0 t/ha per year when using the ESA WC model. This variation (from 5.6 to 6.0 t/ha per year) is relatively small given the many assumptions used in modeling erosional and depositional processes.

Differences in estimates of cropland area in Alekseevskii district did not directly affect an increase or a decrease in the estimated rates of soil erosion. In particular, when using the boundaries of cropland areas on the RMSLC, the minimum estimated rates of soil erosion were obtained, although the cropland area on this map was close to the average value for all the maps. It is likely that the rate of soil erosion averaged across regions is determined by the location of cropland relative to local topography elements rather than by the total cropland area.

It was previously noted that on the UFIS AL map, cropland (cultivated fields) is more fragmented, i.e., adjacent fields are separated by boundaries, unlike those on the ESA WC and GLCLU maps with a much less fragmented pattern of cultivated fields (Fig. 1). The spatial pattern of cropland is taken into account when calculating soil erosion rates. The simulated lines of water and sediment flows are interrupted at the boundaries between neighboring fields, which largely agrees with the behavior of sediment flows in real conditions, when the boundaries of cultivated fields serve as geochemical barriers to the movement of sediments and contribute to the partial or complete redeposition of eroded sediments. As a result, the calculated rates of soil erosion when using the RMSLC and UFIS AL models with highly detailed delineations of cultivated fields turned out to be slightly lower than those based on field boundaries constructed according to remote sensing data with a relatively low spatial resolution (ESA WC and GLCLU).

However, despite the differences in the total area of cropland, the topographic position of cultivated fields, and the degree of detail in their boundaries displayed on the considered maps, the differences in the calcu-

lated rates of soil erosion for the Alekseevskii district turned out to be small (<5%).

We have also calculated maximum deviations from the average rates of soil erosion for separate districts of Belgorod oblast using formula (1). In most of the districts, these deviations were less than 5% (Fig. 3). The strongest deviations were found for Starooskolskii (11%), Volokonovskii (14%), Valuyskii (17%), Gubkinskii (19%), Chernyanskii (20%), and Novooskolskii (27%) districts. The Oskol River flows through all these districts, and all of them are characterized by the high degree of erosional dissection. The dissected rugged relief, on the one hand, contributes to a relatively more fragmented pattern of land use with a large number of small and scattered cultivated fields, which makes their mapping difficult. On the other hand, in conditions of dissected topography, errors in mapping field boundaries when modeling erosion are more pronounced because of larger proportion of slope lands subjected to soil erosion. Consequently, in the case of an overestimation of cropland area under conditions of a strongly dissected relief, the corresponding increase in the calculated rates of soil erosion is more pronounced than that in slightly dissected plain areas, all other things being equal.

We note that there is no direct relationship between the cropland area and the average rate of soil erosion. An increase in the portion of cropland in some districts led to an increase in the calculated rate of erosion, whereas an opposite tendency was observed in other districts. The increase in the rates of erosion is associated with excessive coverage of erosion-prone slope areas by cropland in addition to the actually cultivated land. The decrease in the rates of erosion is associated with the excessive cropland shown on flat areas with low rates of erosion and with the deposition of sediments within the cultivated fields. Thus, not only the area of cropland plays an important role in modeling soil erosion but also the cartographic accuracy of the position of cultivated fields relative to the elements of local topography.

For average estimates of soil erosion by separate districts of Belgorod oblast, a hypotheses regarding the equality of average values obtained from different maps was tested. Average rates of soil erosion calculated from the ESA WC and GLCLU models display a statistically significant difference. However, for the pair of estimates of soil erosion calculated using the UFIS AL and ESA WC models, as well as for the pair of estimates based in the UFIS AL and GLCLU models, the difference is statistically insignificant with a probability of 95%. Thus, the estimates made using the UFIS AL model are closest to the average estimates calculated from the three land use maps; probably, they may be considered the most accurate estimates among the available assessment options.

In general, in Belgorod oblast, the estimated average rates of soil erosion (according to different maps)
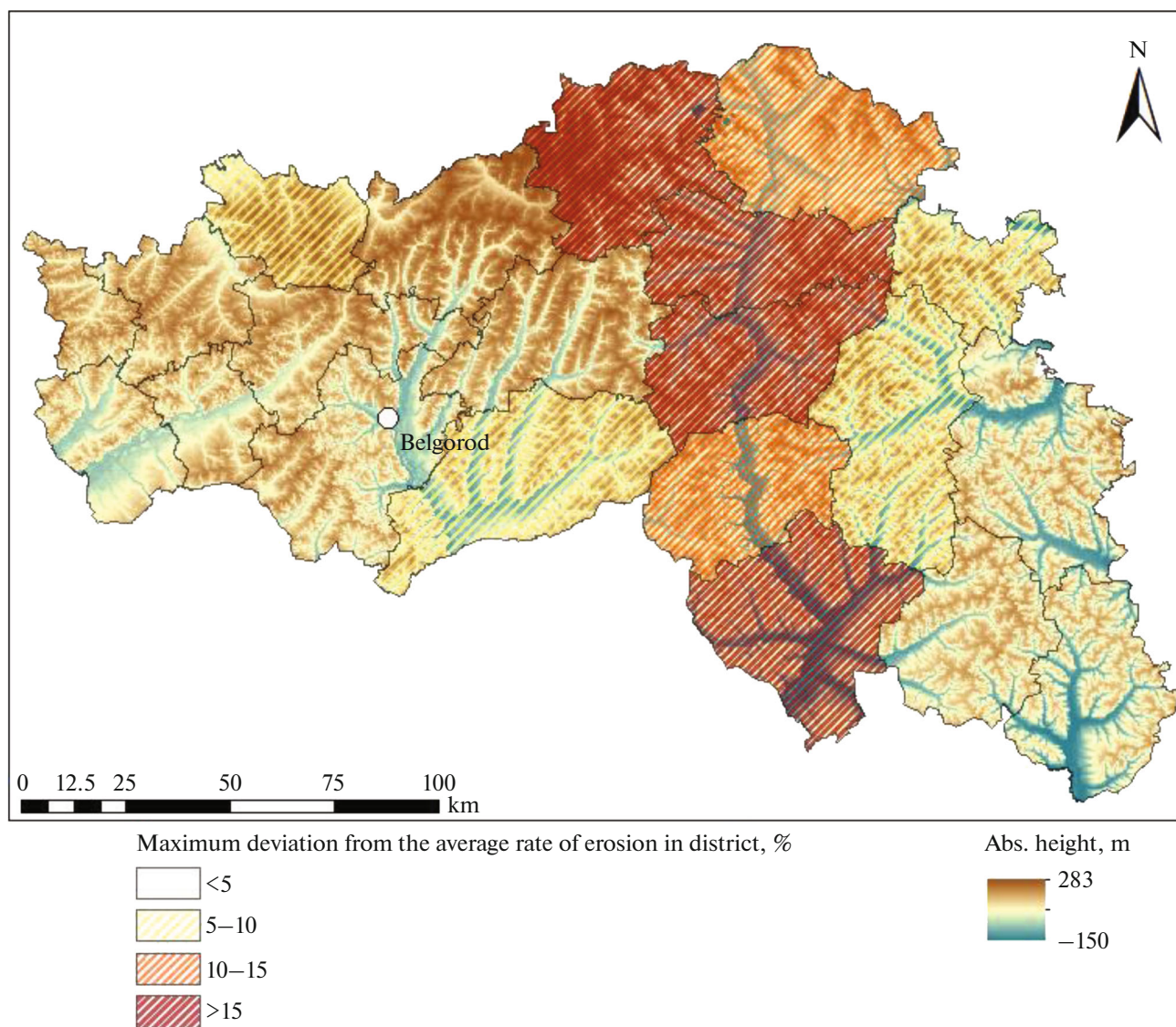
Fig. 3. Deviations of the rates of soil erosion calculated for Belgorod oblast using different maps of cropland from the averaged estimates.

varied from 4.3 to 5.0 t/ha per year. The maximum rates for separate districts (5.0 t/ha per year) were obtained using the ESA WC land use model, and the minimum rates (4.4 t/ha per year) were obtained using the GLCLU model.

The average estimate based on the three land use maps for the entire oblast is 4.7 t/ha per year. The estimate based on the UFIS AL map is very close to the average and equals 4.6 t/ha per year. The maximum deviations from the average estimates of soil erosion for the particular districts for this map are up to 7%. Such fluctuations in estimates of soil erosion rates can be considered as small, because measured average long-term rates of soil erosion may differ by 15−40% depending on certain assumptions and accuracy of the used methods [54]. In some cases, average estimates

obtained by different methods and for different periods may differ by an order of magnitude.

Available literature data on the average long-term rates of soil erosion in agricultural landscapes of Belgorod oblast vary within fairly wide limits. According to regional estimates, the average rate of soil erosion in Belgorod oblast is 3.5 t/ha per year [38]. According to estimates performed for the European part of Russia, it is about 10 t/ha per year [46]. According to [4], it varies in the range of 5−10 t/ha per year. According to [20], it reached 5.1 t/ha per year in the 1980s and decreased by 3.6% (i.e., to 4.9 t/ha per year) in the 2010s.

Thus, the estimates of soil erosion of 4.3−5.0 t/ha per year obtained in our study are completely within the range of earlier made estimates available from Rus-

sian published sources and are generally close to the average values.

Global estimates of soil erosion for Belgorod region differ significantly from the Russian estimates shown above. The latest version of global soil erosion modeling, GLOSEM 1.3, was carried out at high resolution (averaging about 100 m depending on latitude) [35]. This map is available in raster form, which made it possible to take into account the rates of soil erosion separately for Belgorod oblast. According to these data, the cropland area in the oblast is 2.37 million ha, which is by more than 1.5 times higher than according to all the maps used in our study. The average rate of soil erosion for Belgorod oblast according to the GLOSEM 1.3 is 1.2 t/ha per year, which is significantly (>3.5 times) lower than the estimates obtained in our study and almost three times lower than the smallest estimate of soil erosion in Belgorod oblast presented in Russian literature [38]. Thus, global estimates of soil erosion are likely to be significantly underestimated (by a factor of 3–3.5).

Comparative analysis of soil loss volumes. The volumes of erosion losses of soil mean the total volume of soil matter removed beyond the boundaries of the analyzed territory. This indicator is important in calculating sediment balances in general and in assessing the cycle of chemical elements (for example, carbon) and their compounds, in particular. The volume of erosion losses is calculated as the rate of soil erosion (net erosion) multiplied by the area of cropland and are expressed in tons per plot.

Soil loss volumes calculated according to the ESA WC model are maximum in all districts of Belgorod oblast; minimum volumes are obtained when using the GLCLU model. The volumes of erosion losses of soil calculated using the UFIS AL are closest to the average estimates. This is confirmed by testing hypotheses about the equality of average values calculated for individual districts of Belgorod oblast. For the volume of erosion losses, as well as for the rates of soil erosion, statistically significant differences were found in the estimates obtained using ESA WC and GLCLU models. In turn, pairs of soil loss volume estimates using UFIS AL and ESA WC models, as well as UFIS AL and GLCLU models with a probability of 95% do not have statistically significant differences in this indicator.

The maximum deviations from the regional average volumes of erosion losses of soil were calculated by analogy with other estimates using formula (1). The maximum deviations from the average volumes of erosion losses estimated for Belgorod oblast as a whole amounted to 12.9%. In most of districts, deviations from the average volume of erosion losses range from 3 to 11%. The most considerable deviations from the average volume of erosion losses were identified in Volokonovskii (18.4%), Starooskolskii (23.8%), Valuyskii (25.1%), Gubkinskii (25.4%),

Chernyanskii (25.7%), and Novooskolskii (31.0%) districts. Thus, the strongest deviations from the average volumes of erosion losses and from the average rates of soil erosion were found in the same areas with the strongest erosional dissection of the territory (Fig. 3).

According to our estimates, the total loss of soil matter under the influence of water erosion in Belgorod oblast ranges from 6.0 to 7.8 million tons per year. According to national estimates, the mass of soil washed away in the 1980s amounted to 5.9 million tons per year; in the 2010s, it decreased by 9.5%; so, at present, it amounts to 5.3 million tons per year [21].

CONCLUSIONS

The accuracy of determining cropland areas with due account for the percentage of errors of the first ("missed target") and second ("false alarm") types and estimated for Alekseevskii district of Belgorod oblast with the use of different land use maps reaches 10% for the UFIS AL, 16% for the ESA WC, and 17% for the GLCLU maps. Cropland area in Alekseevskii district is about 15 times smaller than cropland area in the entire Belgorod oblast according to all these maps, which allows us to assume that their overall accuracies for Belgorod oblast as a whole are approximately equal. The total of cropland areas coinciding on the UFIS AL, ESA WC, and GLCLU maps (map intersection) for Belgorod oblast is 27% smaller than the total area of cropland shown on at least one of the maps (map combination).

A tendency has been revealed for a greater number of errors in mapping the cropland in the districts with a smaller percent of cropland in the total district area.

The rates of soil erosion and the volume of erosion losses calculated using the UFIS AL map turned out to be closest to the average estimates obtained from the three maps as compared with estimated based on the ESA WC and GLCLU maps. Soil erosion estimates calculated according to the ESA WC map turned out to be maximum in almost all districts of Belgorod oblast, whereas minimum estimates were obtained with the use of the GLCLU map.

Despite the differences in the total cropland area, its position in the relief, and the degree of detail in the boundaries of cropland areas on different maps, the differences in the estimated rates of soil erosion for Belgorod oblast as a whole are relatively small (about 7%). However, in certain areas with a high degree of erosional dissection, the discrepancies in the calculated rates of soil erosion and soil loss volumes reach 27%.

There is no direct relationship between the cropland area and the calculated rate of soil erosion. Cartographic distortion of the boundaries of particular cultivated fields with an increase in the area of cropland has led to an increase in the calculated rates of soil erosion in some districts and to their decrease in other districts.

In Belgorod oblast, cropland area according to different estimates varies slightly: from 1445 to 1586 thousand hectares. Thus, this region of the Russian Federation is largely favorable for modeling soil erosion. However, the accuracy of estimates of the rates and volumes of soil erosion at the regional level, even in such a region, cannot be higher than 85−90%. For the entire Russia, estimates of cropland area vary from 80 million hectares (sown area in 2022) to 132 million hectares in 1990. Consequently, in some regions of the Russian Federation and in the country as a whole, the use of existing maps of cropland can lead to higher errors in soil erosion modeling.

Global estimates of soil erosion [35] for Belgorod oblast are significantly (several times) underestimated relative to estimates published in Russian literature and found in this study.

SUPPLEMENTARY INFORMATION

The online version contains supplementary materials available for authorized users at https://doil.org/10.1134/S1064229323603293.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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