Cartographic-geoinformational estimation of spatio-temporal erosion dynamics of arable soils in forest-steppe landscapes of the Russian Plain

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Abstract The intensity of soil erosion in the forest-steppe landscapes of the Russian Plain was assessed using a cartographic method and GIS. The aim of the research was to devise a method for analysing the spatio-temporal dynamics of soil erosion intensity under conditions of high agricultural production. The intensity of anthropogenic erosion was assessed for the period from 1970 to 2007. These years cover the period of highest intensity of agricultural land use (USSR) and the subsequent period of agricultural loading reduction experienced during the transitional economy of Russia during the 1990s. Spatio-temporal analysis of soil erosion was conducted by the creation of vector thematic erosion maps, generated using the "overlay" cartographic approach. The change in soil erosion contours was estimated for each key soil type.

Key words soil erosion; GIS; thematic maps; dynamics; river basins

INTRODUCTION

The forest-steppe landscapes on the east of the Russian Plain possess favourable agro-climatic resources. In particular, the local soils (chernozems) are fertile and have therefore been used to help support intensive agricultural production. About 70–80% of the local total river basin area is occupied by cropped land. The sample used for this study contained 3331 river basins, 500 of which are more than 90% cultivated, 1100 more than 70%, and only 284 less than 20% ploughed. Extensive cultivation is responsible for accelerated soil erosion and, for this reason, the study region is figuratively called the "erosion pole" of Russia.

DATA

The study area is located within the forest, forest-steppe and northern part of the steppe landscape of the Russian Plain and comprises more than 130 000 km^2. A total of 3331 river basins were included in the analysis and these have an average area of 40 km^2. Information on soil erosion on arable land was obtained for the territory of the Middle Volga, including the basins of the rivers Volga, Vyatka, Kama and Sviyaga. During the last 200 years, arable land cover has increased by up to 40–60% and now comprises about 75–85% of the total river basin area. The period of most intensive agriculture in the region began about 200 years ago. According to archived maps, the landscape zones which have experienced the greatest deforestation and pronounced increase in arable area are the southern forest-steppe and broad-leaved forest landscape zones (Yermolaev, 2007).

The most reliable source of information on the spatial extent of soil erosion on the crop lands of the Russian Federation (and former USSR) is thematic maps. Complete soil erosion mapping of agricultural land within the borders of state farms was undertaken earlier according to the State programme. The basic scale of those investigations was 1:10 000 or 1:25 000, depending on the investigated area. During the soil mapping, about 200–300 soil sections (profiles) were used on the land comprising each farm, with the result that there are thousands of such soil sections across the territories of the Russian Federation (for example, across the territory of Chuvashiya there are 82 215 soil sections). The soil maps were generalized to the scale 1:50 000 (for a municipal regions) and 1:200 000 (for the territory of regions or republics of the Russian Federation). Nowadays, there is an ongoing programme of correction of the early soil maps. The new improved soil maps are being transformed into vector form for a GIS environment. Comparison of vectorised old and new soil maps provides a basis for assessing the dynamics of anthropogenic soil erosion during a medium-term period (from the 1970s to the present day). The main advantages of using the data obtained from soil mapping for the estimation of soil erosion include the continuous coverage at large scales, and the comparison of information assembled over time using consistent cartographic methods.

METHOD

An early classification of eroded soils continues to be used in soil mapping across Russia. The main diagnostic indicators of soil erosion are the loss of the humus horizon (A) and, to some extent, the depletion of humus supply (Egorov *et al.*, 1977). The former criterion is the principal one, because the definition of humus supply is typically based on an insignificant number of soil sections assessed under laboratory conditions.

All soils are subdivided into three key categories: slightly eroded, moderately eroded and severely eroded. The characteristics of these categories for the most widespread soils (grey forest soils and leached chernozems) across the study region can be summarized as:

Grey forest soils: slightly eroded – humus horizons are washed off less than 30% of the area, humus supply is 20–25% poorer than in non-eroded soils; moderately eroded – humus horizons are washed off more than 30%, the transitional humus horizon A_2B_1 is used as crop land; severely eroded – the humus horizons are completely washed off and arable cultivation is undertaken on an illuviated B-horizon.

Chernozems: slightly eroded – humus horizons are washed off less than 30% of the area, humus supply is 10% poorer than in non-eroded soils; moderately eroded – humus horizons are washed off more than 50%, humus supply is 50% poorer than in non-eroded soils; severely eroded – humus A horizon is completely washed off, and partially the upper part of the illuviated B_1-horizon, humus supply is reduced for 75%.

When categories of soil erosion are defined, a thorough consideration of regional standards (soil sections) is required. The selection of such regional standards is essential because of variations in soil forming conditions across the landscape. Usually, in landscape settings of plain relief, standard soil sections are selected on watersheds where there is no surface runoff or sheet erosion and where rain splash does not affect the thickness of the humus horizon. Soil types should also be taken into account when standard soil sections are selected for assessment.

For the study region, the characteristics of standard soil sections were determined as in Table 1.

Table 1 Statistical characteristics of the standard soils (for A+AB horizons) (Yermolaev, 1992).

Soil type	M (cm)	σ	m	CV
Grey forest soil	38.0	6.0	1.46	15.0
Leached chernozem	57.0	5.0	0.62	8.8
Typic chernozem	59.0	6.6	1.19	11.0

M: mean arithmetic mean of horizon; σ: standard deviation; m: mean error; CV: coefficient of variation.

The analysis of the spatial distribution of soil erosion in the eastern part of the Russian Plain (in the Middle Volga River basin) employing a cartographic method was undertaken at two spatial scales: regional (1:200 000) and local (1:10 000).

Regional level A GIS vector map was generated and the outlines of soil types and soil erosion from soil maps (1:200 000) were added to the vector map of the river basins to permit the creation of a geospatial database. A quantitative index of soil erosion intensity in each river basin was created. This index included the area of eroded soils and the corresponding intensity of the processes. The creation of the index presupposes the following:

(a) it should not depend on the river basin area, i.e. it must be relative and dimensionless;
(b) it should be calculated by taking into account the areas of agricultural land;

(c) it should consider the presence of three categories of eroded soils and the varying intensity of soil erosion process for each of them;
(d) it must generate distributions of soil erosion index values close to normal for using parametric methods of analysis in quantitative evaluation (Yermolaev, 2002).

Weighted coefficients for soils with different erosion categories were selected based on detailed analysis of humus supply reduction (t/ha) and the percentage of humus in arable horizons of the most common soils across the study region (grey forest soils and chernozems) by taking into account their granulometric composition. On this basis, the intensity of soil erosion from the slightly to moderately and severely eroded categories changes in the ratio 1:3:5. The final index used for the quantitative estimation of soil erosion in river basins, has the form:

$$E = \left(\left(S_1 + 3 \times S_2 + 5 \times S_3\right) / S_{al}\right)^{1/2} \quad (1)$$

E is soil erosion intensity index; S_1, S_2, S_3 are the areas of slightly, moderate and severely eroded soils respectively, km^2; and S_{al} is agricultural land area (crop land, km^2). The sample of 2177 river basins generated for the study area was assessed for normality for subsequent statistical analysis.

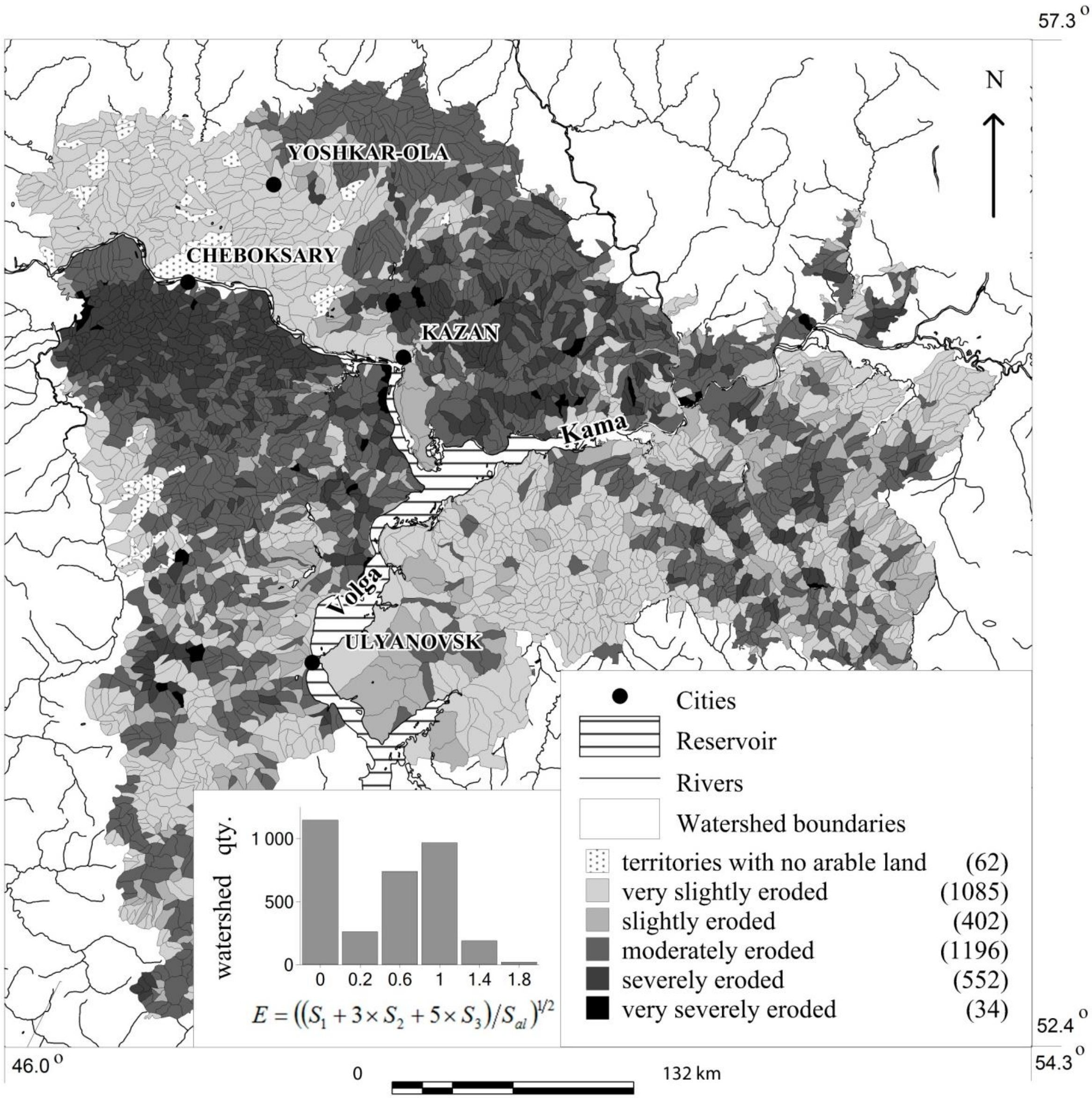

Fig. 1 Soil erosion intensity across the Russian Plain (Middle Volga River basin).

RESULTS

Regional level

The soil erosion vector map for the study region is shown in Fig. 1. The soil erosion index (*E*) values ranged from 0 to 2.24. The ranges of the index value for the soil erosion categories were: (1) territories with no arable land; (2) very slightly eroded (0.0); (3) slightly eroded (0.0–0.5); (4) moderately eroded (0.5–1.0); (5) severely eroded (1.0–1.5); and (6) very severely eroded (more than 1.5). A total of 62 river basins with no arable land were identified. These were mainly forested (mean forest cover is 98.3%) and swamp lowlands. Almost a third of the river basins across the study area (n = 1085) were categorized as very slightly eroded. These are situated in lowlands including the Tatarstan and Mary-Al republics. This category of soil erosion usually develops in areas with high average forest cover (39.6%) and moderate anthropogenic pressure (cropland 47.1%, urban settlements 5%). Gully density is 0.166 km/km^2. Slightly eroded soils were registered in 402 of the study basins (e.g. basins of rivers Sviyaga and Syzran). Gully density in these areas is 0.311 km/km^2. Low forest (20.4%) and high agricultural cover (arable areas occupy about 63.2%) are typical for these areas. River basins (n = 1196) classified with moderate soil erosion represented the largest group for the study area. Moderate soil erosion predominantly occurs on elevated terrains (heights between 180 and 240 m) where forest cover is 5–25%, mean gradients are from 1.5 to 2° and the percentage of meadow cover is more than 12%. Gully density is 0.308 km/km^2. Severely eroded soils were identified in 552 river basins. In these areas, crop land occupies 61.7%, small forest cover less than 10% and rural settlements 8.5%. Gully erosion is more widespread, with gully density estimated at 1.5 times the study region mean (0.499 km/km^2). About 1% (n = 34) of the river basins were categorized as having very severely eroded soils. Gully density is very high in these areas, rising to 0.618 km/km^2.

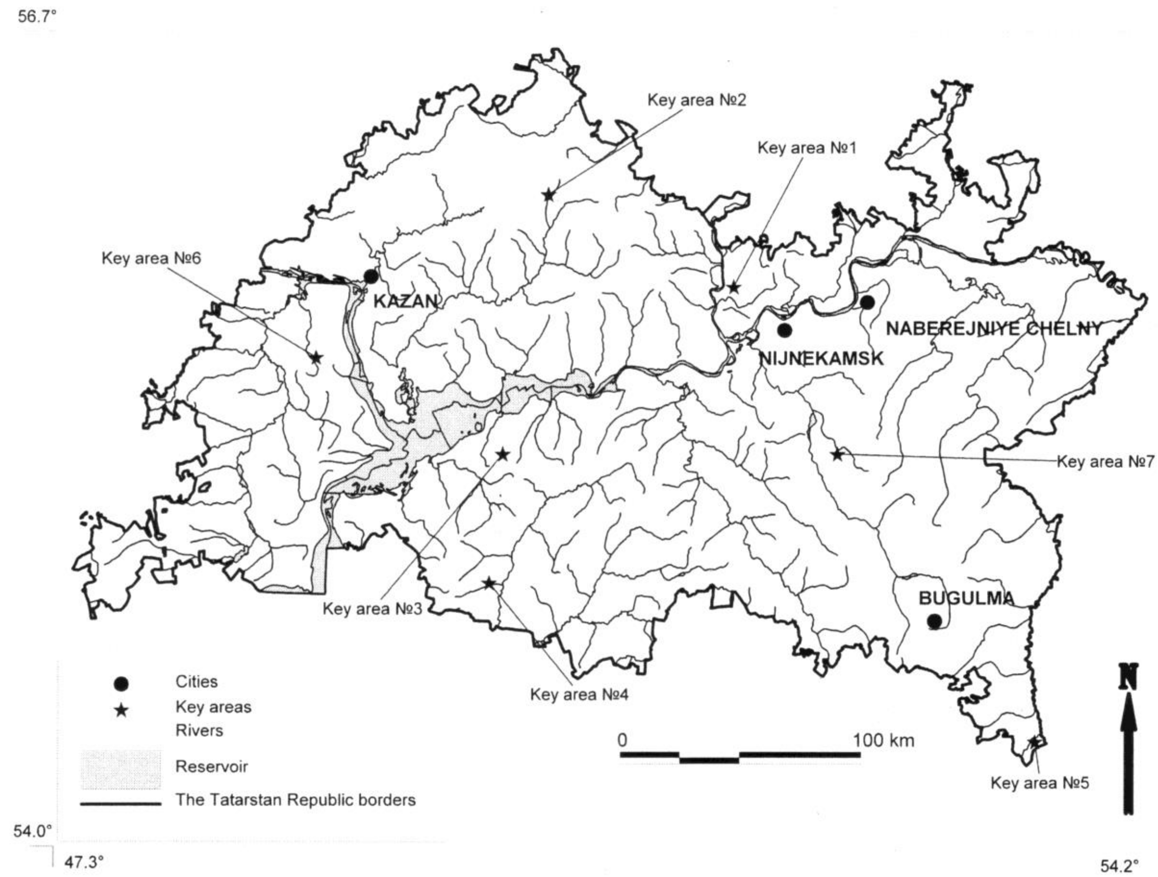

Fig. 2 Areas of the Tatarstan Republic used for the local-scale soil erosion mapping exercise.

Local level

Soil maps of scale 1:10 000 were used for the estimation of soil erosion intensity at the local level. Areas in the Tatarstan Republic are used as an example in this paper. The selected representative areas (Fig. 2) met the following key requirements:

(a) they reflected typical landscape features (e.g. soil and relief) in the study area for assisting subsequent data extrapolation;
(b) repeat soil maps were available (nowadays repeat soil mapping is only undertaken in a few regions of the Tatarstan Republic and previous data for some regions has been lost since the archives are in poor condition);
(c) data must be available for supporting the more detailed level of generalization for the analysis of factors (mostly relief) determining soil erosion spatio-temporal dynamics (Avvakumova & Yermolaev, 2011).

Old paper soil maps and new corrected vector soil maps were employed as initial data for our investigation (Table 2). Cartographic materials were processed and analysed using GIS MapInfo.

Table 2 The initial data used for the local level of investigation (1:10 000).

Key areas	Year of the first soil survey	Year of repeat soil survey	Key areas	Year of the first soil survey	Year of repeat soil survey
No. 1, 5235 ha	1974	2005	No. 5, 4866 ha	1967	2005
No. 2, 4556 ha	1971	2001	No. 6, 3663 ha	1983	2001
No. 3, 4132 ha	1985	2001	No. 7, 6669 ha	1974	2007
No. 4, 3171 ha	1978	2003			

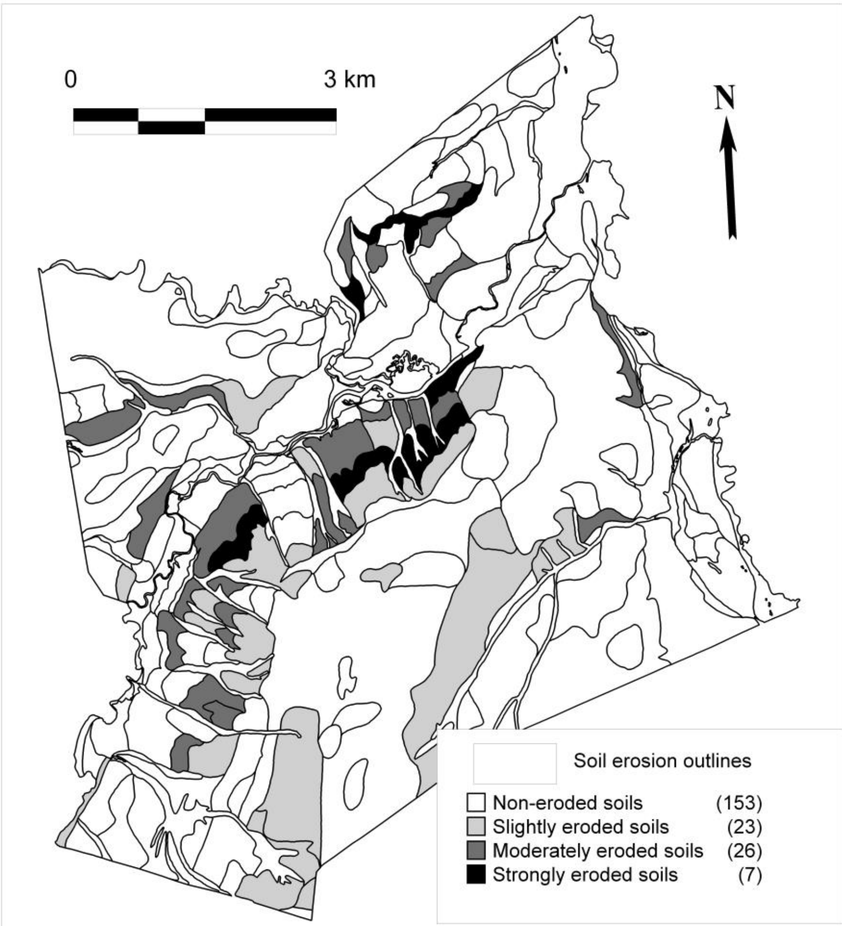

Fig. 3 Example local soil erosion map (1967 soil survey).

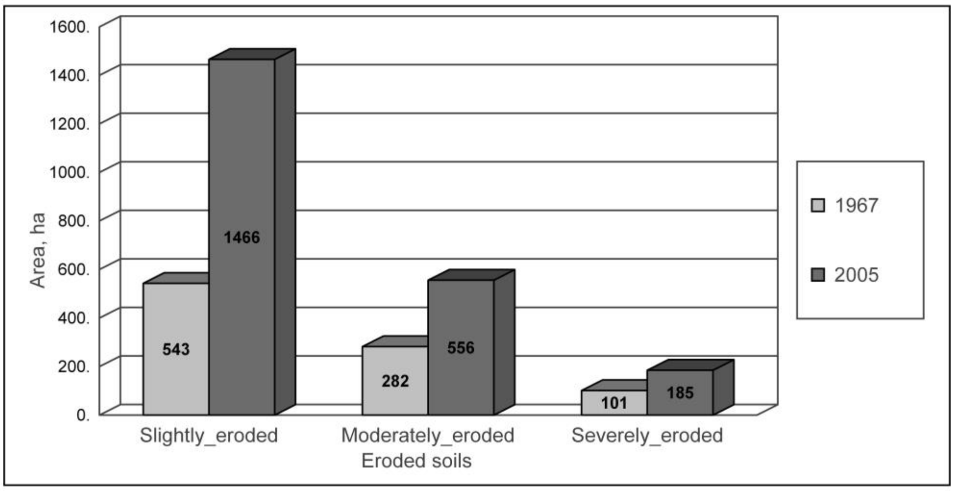

Fig. 4 Change in soil erosion on the basis of the repeat soil surveys.

An example local soil erosion map is shown in Fig. 3. Repeat soil erosion maps, one for each of the two for time periods (Table 2) were created to provide a basis for analysing the spatio-temporal dynamics of soil erosion. Figure 4 presents the results of the analysis and shows the change in the extent of the soil erosion categories. The results of this analysis were extrapolated to areas with similar landscape attributes.

CONCLUSIONS

For the first time in Russia, a cartographic method for estimating soil erosion dynamics over the past 40–50 years on arable land using thematic maps and GIS has been developed and applied to the Russian Plain. Based on the soil maps of arable land across Russia, an integrated index, which reflects soil erosion intensity in the river basin, was developed. On this basis, a regionalization of soil erosion was produced. According to the cartographic data generated, the maximum intensity of soil erosion was experienced on the elevated plains of mixed forest and forest-steppe zones, whereas the minimum intensity was experienced in the southern taiga and lowland forest-steppe zone. The assessment of soil erosion remains important given the need to feed a growing human population.

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