Trend of Soil Erosion Processes within the Southern Half of the Russian Plain for the Last Decades

V N Golosov¹,², O P Yermolaev¹, G R Safina¹, K A Maltsev¹, A V Gusarov¹ and I I Rysin¹,³

¹ Institute of Environmental Sciences, Kazan Federal University, 18, Kremlevskaya str., 420008, Kazan, Russia
² Faculty of Geography, Lomonosov Moscow State University, 1, Leninskie Gory, 119991, Moscow, Russia
³ Institute of Natural Sciences, Department of Ecology and Natural Resources Management, Udmurt State University, 1, Universitetskaya str., 426034, Izhevsk, Russia

E-mail: gollossov@gmail.com

Abstract. Complex approach is applied for assessment of recent trends of sheet, rill and gully erosion in different landscape zones of study area. Investigation is undertaken in 6 selected sectors (area of each transect is about 6-10 thousand km²), uniformly distributed over the area of the Russian Plain. Changes of the different factors, including some meteorological and hydrological parameters, land use change, USLE C-factor, were determined for the period 1980-2015. A set of field methods was used for quantification of sediment redistribution rates for the key small catchments. It was found that erosion rate decreased in forest and forest-steppe zone. Gully density decreases considerably in all landscape zones. The reduction of surface runoff from cultivated slope during snow-melting is the main reason of decreasing of sheet, rill and gully erosion rates in the forest, forest steppe and the north of steppe landscape zones. Increasing the proportion of perennial grasses in crop-rotation is the other factor of serious reduction of erosion processes in the forest zone.

1. Introduction

The most part of croplands is located in the Southern part of Russian Plain within south part of forest, forest-steppe and steppe landscape zone. It is area with relatively short history of intensive agriculture with duration from 4-5 centuries in the center part around Moscow in forest zone up to about 120-150 years on the south and south-east within the steppe zones [1]. The highest area of cropland in the most productive forest-steppe zone was reached at the end of 19th century after land reform when very steep slopes were cultivated, and maximum of gully erosion rates was reached immediately [2]. During the 20-th century cropland area was relatively stable within the forest and forest-steppe zone while it enlarged in the steppe zone because of virgin lands cultivation during 1950th.

Latest quantitative assessment of erosion rates for the entire European Russia was undertaken at the beginning of 1980th based on application of modified version of USLE and State Hydrological Institute model for evaluation of erosion rate during rain-fall season and snow-melting respectively [3]. Results of model calculations were verified based on the monitoring data of soil losses during snow-melting and
evaluation of total soil losses in the small field ponds [4, 5]. It was shown that model calculations are in a good agreement with actual soil losses.

More than 35 years passed since the last quantitative assessment of soil erosion losses from croplands of the Russian Plain. Considerable economic changes had occurred after USSR collapse in 1991 with following land use and crop-rotation changes in some landscape zones of European part of Russia. In addition, global warming is affecting on dynamic of meteorological characteristics in the different parts of the world since the middle of 1970th. It is very likely that both land use and climate changes influenced on the soil erosion rates on the croplands of the Russian Plain. The objectives of this paper are evaluation of the trend of different erosion processes based on application of erosion models, interpretation of aerial photographs and satellite images and application of $^{137}$Cs techniques for the dating of sediment redeposited in the valley bottoms of the first- order agricultural catchments located in the different landscape zones of the Russian Plain.

![Map of the European part of Russia with location of studied transects.](image_url)

**Figure 1.** Map of the European part of Russia with location of studied transects.

2. Material and methods

2.1. Study area

The Russian Plain occupies area from the Caucasus mountain foothills and the Caspian Sea on the south, the Ural Mountains on the east, Arctic Ocean and White Sea on the north. Western boundary of the study area is similar with the western border of the Russian Federation (figure 1). Despite of quantitative assessment of soil losses done for the entire Russian Plain, the most attention was given to the southern half of studied territory to the south from the line Bryansk- Moscow – Nizhniy Novgorod – Kazan –
Perm because the most part of croplands is located within the given territory. The Northern half of the Russian plain is located in tundra, taiga and mixed deciduous-coniferous forests landscape zones with mostly moraine relief, poor soils with low content of organic matter, proportion of croplands from 0% to 20% (of the total area) and the significant proportion perennial grasses in crop rotations.

The southern half of the Russian Plain is located mostly in forest-steppe and steppe landscape zones where soils formed on the loess with high organic content dominate. So the proportion of cropland changes in the range 35-85%, and row crops (corn, sunflower, sugar beet, buckwheat etc.) are the significant components of the crop-rotation. A temperate continental climate with relatively cold winter and warm summer is typical for the most part of the Russian Plain. Total (snow + rain) annual precipitation reduces from the north-west to the south-east territory from 650 to 350 mm with increasing of evaporation in the same direction. So droughts are observed very often in particular in the south-eastern part of the steppe zone. During the most part of the 20th century soil erosion during snow-melting is observed within the most part of the Russian Plain with maximum on the north of the forest-steppe zone while soil erosion during rain storms is widespread mostly in steppe and south part of forest-steppe zone. Sometimes extremely heavy rains lead to severe erosion even in the forest zone [5].

2.2. Methods

Six transects located in different landscape zones of the southern part of Russian Plain were selected for the more detail assessment of possible trend of erosion rates during last decades (figure 1). The evaluation of erosion process trend was undertaken for the key river basins located within the each transect and for the small agricultural catchment located within each river basin. Complex approach was applied for evaluation of contemporary trend of the sheet, rill and gully erosion within each transect. Field methods and techniques are used for determination of gully headcut retreat rate and sediment redistribution rates within small first-order catchments, including: large-scale geomorphological mapping, 3-D scanning, detail topographical survey, 137Cs technique, soil-morphological method and others. A set of high-resolution satellite images including IKONOS, GeoEye-1, Spot, World-View was used for evaluation of land-use transformations, gully head density, length of active gully within the key river basins selected within each transect. In addition, long-term monitoring data of water discharges in the key studied basins were collected. Particular attention was given to analysis of water discharges during spring floods, as an indicator of the surface runoff from cultivated slopes in this period of year.

Calculation of erosion rates and total soil losses from croplands for different landscape zones of the Russian Plain and for the key river basins within each transect was done using modified version of USLE (rain-fall period) and State Hydrological Institute model (period of snow-melting). Rainfall erosivity factor was re-calculated for the 2012 based on linear relationship between layer and rainfall erosivity of individual rain [6]. Crop rotation coefficients for rainfall and snow-melting periods were calculated using statistical data about areas under different crops and method of cultivation and rainfall erosivity index for different months for each region. Changes of arable lands area were taken into consideration. Information about land-use changes and land area under different crops for different regions of Russia for period since USSR collapse was collected from Russian Federal State Statistics Service. Particular attention was given to evaluation of croplands dynamics in different landscapes for the period since 1991 [7]. Additional independent sources of information were used for correction of possible mistake in official statistics [8]. LS factor was calculated separately on 1985 and 2015 for the cultivated fields taking land use changes into consideration [9]. All other parameters were taken from data base constructed in a period of erosion rate calculation for the Russian Plain in 1980.

3. Results and discussion

Changes of the climate and land-use led to different changes of erosion rates and the total soil losses in different landscape zones of the Russian Plain. According to previous assessment the most considerable reduction of both erosion rate and the total soil losses was found for the different parts of the forest zone [10] (table 1).
Table 1. Changes of mean annual soil erosion rate and total soil losses in 1980 and in 2012 calculated using modified version of USLE (rain-storm erosion) and State Hydrological Institute (erosion during snow-melting) models [11].

| Landscape zone of European part of Russia (without mountain area) | Mean annual soil erosion rate in 1980, t ha\(^{-1}\) year\(^{-1}\) | Mean annual soil erosion rate in 2012, t ha\(^{-1}\) year\(^{-1}\) | Change of mean annual soil erosion rate\(^a\), \(\%\) | Total soil losses in 1980, 10\(^3\) t | Total soil losses in 2012, 10\(^3\) t | Change of total soil losses\(^*\), \(\%\) |
|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Northern and middle taiga zone                                 | 6.5                                                           | 4.0                                                           | -38.4                                                         | 6131.5                                                         | 1808.8                                                         | -70.5                                                         |
| Southern taiga zone                                            | 7.3                                                           | 4.1                                                           | -44.0                                                         | 145031.9                                                      | 35965.9                                                      | -75.2                                                         |
| Forest zone, total                                             | 7.3                                                           | 4.1                                                           | -43.8                                                         | 151163.4                                                      | 37790.9                                                      | -75.0                                                         |
| Forest-steppe zone                                             | 4.1                                                           | 3.3                                                           | -19.4                                                         | 136449.7                                                      | 79277.3                                                      | -41.9                                                         |
| Steppe zone                                                    | 3.9                                                           | 4.63                                                          | 18.7                                                          | 148617.8                                                      | 127662.7                                                      | -14.1                                                         |
| Total European Russia                                          | 4.7                                                           | 4.0                                                           | -15.0                                                         | 436230.9                                                      | 244830.9                                                      | -43.9                                                         |

\(^a\) Relationship between 1980 and 2012

There are several reasons of such trend, including reduction of arable land area, changes in crop rotation and serious decreasing of surface runoff during snow-melting. Also some reduction of erosion rates was determined for the forest-steppe zone with more serious decreasing of the total soil losses mainly because of reduction of arable land area. Also it is more likely that possible increasing of soil losses during rain-storm season does not compensate the decreasing of soil losses during snow-melting. However, soil erosion rate increased in the steppe zone according to results of the model calculation because of increasing of frequency of the rain-storms with layer of 40-50 mm. But the total soil losses in steppe zone also decrease because of reduction of arable land area. It is necessary to emphasize that area of arable lands partially restored since 2012 due to the plowing of previously abandoned lands since 2012.

Table 2. Changes of mean annual soil erosion rate for the key river basins in 1985 and 2015.

| River basin | Basin area, km\(^2\) | Landscape zone, transect | Mean annual erosion rate, \(t\ ha\(^{-1}\) year\(^{-1}\) | 1985 year | 2015 year | Reduction of erosion rate, \(\%\) |
|-------------|----------------------|--------------------------|----------------------------------------------------------|-----------|-----------|-------------------------------|
| Izh         | 2508                 | Forest, 1*               | 4.6                                                      | 4.4       | 4.0       | 4.0                           |
| Mesha       | 4354                 | Forest; forest-steppe, 2 | 7.8                                                      | 6.8       | 12.8      |                               |
| Ulema       | 881                  | Forest-steppe, 2         | 5.8                                                      | 5.0       | 13.8      |                               |
| Veduga      | 1193                 | Forest-steppe 3          | 5.6                                                      | 5.6       | 0         |                               |
| Medveditsa  | 3611                 | Forest-steppe; steppe, 4 | 2.6                                                      | 1.6       | 38.5      |                               |
| Samara      | 2874                 | Steppe, 5               | 2.7                                                      | 2.3       | 14.8      |                               |

*Here and further – transect number, see figure 1.*

Results of calculation of the soil erosion rates show the trend of reduction of soil losses for the most river basins (table 2). The main reason of soil erosion rates decrease is serious decline of surface runoff from the cultivated slopes during snow-melting period. So the soil losses during snow-melting in particular in forest-steppe zone and in the northern part of steppe zone became very close to zero. In addition, some input into reduction of soil erosion rates was associated with decrease of LS factor due to abandonment of cultivated lands. Only the Veduga River basin, located in the western part of the forest-steppe zone, is characterized by the lack of any trend. This territory is characterized by increasing frequency of strong rainfalls [11], which should lead to increase of the rainfall erosion.
Results of the detailed assessments of sediment redistribution rates for periods of 1963-1986 and 1986-2015 at the key catchments, located in the Veduga and the Mesha River basins, were used for verification of the results of soil erosion rate calculations within the studied river basins. Both key catchments are characterized by a high proportion of cultivated land, which, according to the available evidence (topographic maps, aerial photographs, satellite imagery and data archives), has not changed appreciably since the 1950s. Both bomb- and Chernobyl-derived $^{137}$Cs were used as chronological markers for documenting changes in soil erosion rates on croplands during the last 50-55 years in key catchments. The sediment accumulation rates in the dry valley bottoms reflect the intensity of soil erosion on the slopes of the dry valley catchments [12], [13]. Eight $^{137}$Cs depth profiles located in representative cross-sections along the dry valley bottoms have been used to document sediment accumulation rates at key catchments. It was established that the mean annual sedimentation rates had reduced 4-5.4 times in both key catchments (table 3). In case of Mesha River basin key catchment is located in area with slightly higher erosion rates as compared to mean values for the entire river basin (table 2).

The calculated mean annual erosion rates had reduced from 8.4 to 7.1 t ha$^{-1}$ (the Mesha key catchment) and from 5.5 to 5.0 t ha$^{-1}$ (Veduga key catchment) in 1963-1986 and 1986-2015 respectively. It is very likely that soil losses were underestimated for 1963-1986 due to incomplete estimation of erosion losses during snow melt. The ephemeral gully erosion usually had formed in the hollow bottoms due to water concentration, and this type of erosion was not calculated by the SHI model. Soil losses from cultivated hollow catchments are almost one order magnitude higher as compared to soil losses from slope without hollows according to field monitoring data obtained as a result of 15- years’ observations during snow-melt in the southern part of the forest zone of the European Russia [4].

**Table 3.** Estimates of mean annual sedimentation rates in dry valley bottoms at the key catchments for different periods based on interpretation of $^{137}$Cs depth profiles.

| Dry valley location | Landscape zone, transect | Co-ordinates | Mean annual sedimentation rates, cm yr$^{-1}$ for indicated time interval | Reduction of sedimentation rate |
|---------------------|--------------------------|--------------|-------------------------------------------------------------------------|---------------------------------|
| Veduga River basin  | Forest and forest-steppe, 3 | 51.760539N 38.602139E | $2.0 \pm 0.2 \quad 0.5 \pm 0.05$ | x 4 |
| Mesha River basin   | North of forest-steppe, 2 | 55.645670N 49.646451E | $1.4 \pm 0.15 \quad 0.26 \pm 0.05$ | x 5.4 |

**Table 4.** Gully density in some key river basins of different landscape zones of the European Russia in 1990 and 2015 [14].

| River basin | Landscape zone, transect | Gully density, km$^{-2}$ | 1990 year | 2015 year |
|-------------|--------------------------|--------------------------|------------|-----------|
| Mesha       | South of forest, forest-steppe, 2 | 0.56 | 0.04 |
| Ulema       | North forest-steppe, 2 | 0.8 | 0.09 |
| Veduga, Devitsa 1, Devitsa 2 | Forest-steppe, 3 | 0.8 | 0.02 |
| Medveditsa  | North steppe, 4 | 0.43 | 0.01 |
| Samara      | Steppe, 5 | 0.26 | 0.02 |

Quantitative assessment of the gully density dynamics for the key river basins indicates the sharp reduction of gulling (Table 4). It is another confirmation of the reduction of erosion processes intensity mostly due to the considerable decrease of the surface runoff during snow-melting in the last decades. It is well-known that the main factor of gully head retreat rates for the most part of landscape zone of Russian Plain (except for the south of steppe zone) is intensity of the surface runoff during the snow-melt [15]. The similar trend of gully erosion rates decrease was found as a result of long-term monitoring of gully head (about 150) in different parts of Vyatsko-Kamskoe interfluve area for per 1978-2015 (Rysin et al., 2017).
The other confirmation of serious reduction of surface runoff from the cultivated slopes during last decade is the decrease of the maximum water discharges of small rivers located within transects 1-5 since the beginning of the 1980s when air temperature began to increase due to climate change (Figure 2). At the same time minimum water discharges observed during summer season increased during the same decades [16]. The reason is increasing ground water table due to growth of water infiltration during spring snow-melting and winter thaws.

At least, the results of monitoring the surface runoff from cultivated lands undertaken at the Novosil experimental station (Orel region, the north of forest-steppe zone) show that the coefficient of water surface runoff decreased from 0.5 for period from 1955-1980 to <0.1 since the late 1990th due to serious reduction of the mean depth of the frozen soil [17].

However, results of the model calculations for the entire steppe zone [11], [10] contradict evaluation of the erosion rates trend for the key river basins (Table 1 and 2). This contradiction may be due to the spatial irregularity of the soil erosion during rainfall season which prevails in the steppe zone. In particular, this assumption is confirmed by the results of estimating the trends of rain frequency with different precipitation layers. However, the results of field investigation within small catchments and the evaluation of the gully density dynamics in the Medveditsa and the Samara River basins indicate that clear decrease trend of the soil erosion rates is observed as compared to the two time windows (1963-1986 and 1986-2016). It is necessary to say that results of the $^{137}$Cs analysis of samples taken within small catchment in the Kalaus River basin are not ready yet.

4. Conclusions
Application of erosion models enables to identify the erosion rates trends for the typical river basins located within the different landscape zones of the southern half of the Russian Plain. The reduction of the erosion rates was determined for the most river basins with the exception of the Veduga River basin, located in the western part of the forest-steppe zone. It is more likely that serious reduction of the soil losses during snow-melting due to decrease of the surface runoff from the cultivated slope is the main reason of negative trend of the mean annual erosion rates. This assumption is in good agreement with the results of monitoring observations of the river runoff which indicate a sharp drop in maximum water discharge during floods and an increase in minimum water flow in summer low water. Field verification of the model calculations on the small agricultural catchments based of the evaluation of sedimentation
rates for the two time windows (1963-1986 and 1986-2015) confirm the identified trend for the previously mentioned landscape zones. The lack of changes of erosion rates in the Veduga River basin can be explained by some increase of soil losses during rainfall season in the last decades due to increase of number of heavy rains. Some uncertainty about the trend of the erosion rates in the southern and western parts of the steppe zone still exists.

Acknowledgements
The work was supported by the Russian Science Foundation (project No. 15-17-20006).

References
[1] Sidorchuk A Yu and Golosov V N 2003 Hydrological processes 17(16) 3347–3358
[2] Veretennikova M V, Zorina E F, Koval’ev S N, Lyubimov B P, Nikol’skaya I I and Prokhorova S D 2006 Geography of gully erosion (Izd-vo MSU, Moscow) p 324
[3] Laronov G A 1993 Water and wind erosion: the main principles and quantitative estimates. (Mosk.Univ. Publ. House: Moscow) (in Russian)
[4] Litvin L F 2002 Geography of soil erosion on agricultural lands of Russia (IKC Akademkniga, Moscow) p 255 (in Russian)
[5] Golosov V N 2006 Erosion and deposition processes in river basins of cultivated plains (GEOS, Moscow) p 296 (in Russian)
[6] Kanatieva N P, Krasnov S F and Litvin L F 2010 Eroziya pochv i ruslovye processy 17 14–27 (in Russian)
[7] Rosstat 2015 Russian Federal Service of State Statistics (Moscow, Russia) Available from: http://www.gks.ru
[8] Lyuri D I, Goryachkin S V, Karavaeva N A, Denisenko E A, Nefedova T G 2010 Dynamic of Agricultural lands in Russia in XX century and postagrogenic restoration of vegetation and soils (GEOS, Moscow) p 416 (in Russian)
[9] Ivanov M A 2017 Changes of cropland area in the river basins of the European part of Russia for the period 1985-2015 years, as a factor of soil erosion dynamics. This volume
[10] Golosov V, Gusarov A, Litvin L, Yermolaev O, Chizhikova N, Safina G and Kiryukhina Z 2017 Integrating monitoring and modelling for sediment dynamics Okehampton, UK, 11–15 July 2016, Proc. IAHS (Copernicus Publications) eds A Collins, M Stone et al vol 375 23–27
[11] Litvin L F, Kiryukhina Z P, Krasnov S F and Dobrovolskaya N G 2017 Pochvovedenie 11 1390–1400
[12] Golosov V N 1998 Geomorphologie Relief, Processus, Environnement 1 53–64
[13] Golosov V N, Walling D E, Konoplev A V, Ivanov M M and Sharifullin AG 2017 Application of bomb- and Chernobyl-derived radiocaesium for reconstructing changes in erosion rates and sediment fluxes from croplands in areas of European Russia with different levels of Chernobyl fallout J. Environment Radioactivity (in press, Available online 18 August 2017)
[14] Medvedeva R A, Golosov V N and Yermolaev O P 2017 Spatial-temporal assessment of gully erosion in zone of intensive agriculture, European part of Russia Geography and Natural Resources (in press)
[15] Butakov G P, Zorina E F, Nikol’skaya I I, Rysin I I, Serebrennikova I A and Yusupova V V 2000 Erozionnye i ruslovye processy 3 (Moscow, MSU) 52–62
[16] Kireeva M B, Frolova N L, Windle F, Dzhamalov R G, Rets E P, Povalishnikova E S and Pahomova O M 2016 Geography, environment, sustainability 9(4) 33–47.
[17] Petelko A I, Golosov V N and Belyaev V R 2007 Proceedings of the 10-th international symposium on river sedimentation (Moscow) vol 1 pp 311–316