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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Assessment of the Trend of Degradation of Arable Soils on the Basis of Data on the Rate of Stratozem Development Obtained with the Use of ^{137}Cs as a Chronomarker

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Abstract—A new approach for determining the trend of changes in the rate of degradation of arable soils is suggested. It is based on the assessment of volumes of soil material eroded from arable fields and accumulated on the bottoms of first-order valleys during two time intervals: 1954(1963)–1986 and 1986–2015. For dating of this material, ^{137}Cs of global fallout and Chernobyl fallout are used. This approach in combination with a detailed morphometric characterization of the valley bottoms, the pathways of sediment transport from the fields, and the morphology and composition of the sediments accumulated on the bottoms makes it possible to give reliable estimates of the volumes of soil loss from tilled slopes. The benchmarks of 1963 and 1986 are related to maximum ^{137}Cs fallout during nuclear bomb testing and immediately after the Chernobyl accident. As an example, the rates of formation of stratozems (stratified aggraded soils formed due to accumulation of eroded sediments) within the first-order catchment of the Veduga River basin (Voronezh oblast, Russia) are analyzed. The results of the study indicate that the mean annual rate of soil loss from arable fields of the catchment in 1986–2015 was at least two times lower than that in the preceding period from 1954 (the beginning of the global fallout) to 1986 (the Chernobyl accident).

Keywords: soil degradation, erosion, Stratozems, sedimentation, chronomarker ^{137}Cs, first-order catchment, Voronezh oblast

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INTRODUCTION

Water erosion and accumulation of sediments on arable lands are the major processes of the soil cover transformation on plain territories of the European part of Russia (EPR). The manifestation of these processes is highly sensitive to hydrological and climatic changes, including those related to the global climate change. In the EPR, the global climate warming has been clearly pronounced in the recent decades [19]. Since the mid-1990s, river discharges during spring floods have become lower because of warmer and less snowy winters in comparison with those in the previous decades [24]. Economic conditions after the breakdown of the Soviet Union led to considerable changes in the land use with a sharp reduction in the cropland area, especially in 1991–2005 [15]. The abandoning of former plowlands mainly affected the forest zone of the EPR; however, this was also observed in the forest-steppe and steppe zones. In recent years, cropland area in the steppe and forest-steppe zone has been partially restored. However, it remains lower than that in the 1980s. These changes in the climatic characteristics and land use could not but affect the intensity of erosion on tilled slopes, which largely controls the degree of soil degradation. However, no direct observations over the rate of soil loss from arable fields on slopes have been conducted in the past decades. At present, soil-erosional surveys that were performed on the regular basis in the earlier years are no more conducted. As a result, it is difficult to give a quantitative estimate of the impact of climatic and economic factors on the intensity of soil degradation caused by erosion.

The aim of this study is to develop a new approach toward quantitative assessment of current trends in erosion-induced soil degradation on arable lands of small catchments on the basis of data on ^{137}Cs chronomarkers making it possible to date sediment sequences accumulated in the bottoms of first-order valleys adjacent to cultivated fields. These sediment sequences represent stratozems (Stratozems)—layered soils with a well-developed aggraded part consisting of soil materials washed off from the fields.

GENERAL METHODOLOGICAL PRINCIPLES

The erosion of soil material from arable fields is accompanied by the redistribution of sediments. Some

Table 1. Generalized data on sediment redistribution within plowed fields on slopes of different shapes as determined by different methods [6], % of the total soil loss

Types of slopes and slope catchments	Rill method	Radiocesium technique, global ^{137}Cs	Pedomorphological method	Average
With hollows, gentle	34–39	40–45	25–63	41
With hollows, steep	–	20–40	15	22.5
Concave	50–60	80	–	68
Uniform	35–45	25–65	13	29
Convex, steep	10	20	10.5	13.5
Convex, moderately steep	15–45	–	–	(30)
Convex, gentle, or with artificial levees at the foot of cultivated part of slope	55–70	75	–	69
Total	39	49	(20)	39

part of the eroded material is redeposited within the fields with the maximum manifestation of this process in places of flattening of the slopes and near the lower boundary of the fields. In the zones of sediment redistribution, the areas of eroded and aggraded soils are formed. These areas are relatively stable in time, though in the case of the high intensity of soil erosion they may considerably expand and, finally, change configuration of the slope. According to available estimates, the portion of material accumulated on the fields within the slope varies from 10 to 40% of the total volume of the eroded soil material (Table 1). The morphology of tilled slopes predominating in the EPR does not favor the accumulation of the eroded material within the slopes; the portion of sediments redistributed within the fields on the slopes is no more than 10–15% of the total volume of transported sediments [6]. Thus, a larger part of the soil material removed from the fields is transported beyond the fields and accumulates in the first-order dry valley bottoms.

The rates of accumulation of soil sediments in the bottoms of the valleys immediately adjacent to the slopes can be determined with the use of ^{137}Cs as a chronomarker. This is a long-living isotope of artificial origin. It appeared in the environment with the beginning of nuclear bomb testing in the atmosphere in 1954. In the northern hemisphere, there were two maximums of nuclear bomb tests in 1958 and 1962. After them, with a time lag of up to one year [13], the fallout of ^{137}Cs reached its maximum (Fig. 1). In 1963, the Partial Nuclear Test Ban Treaty was signed. It prohibited test detonations of nuclear weapons in the atmosphere. Since that time, the fallout of ^{137}Cs has been decreasing. The removal of ^{137}Cs from the lower atmosphere took place upon the development of cumulonimbus clouds and rainfall. Falling onto the soil surface, ^{137}Cs was rapidly and firmly fixed by the soil particles, and its further migration was only together with these particles [31]. The fallout of ^{137}Cs in 1954–1980s was related to nuclear weapons tests in the atmosphere; it is referred to as global or bomb-induced fallout. Local and regional fallouts of ^{137}Cs related to accidents on industrial factories and power plants are known under the names of the places of these accidents. The Chernobyl Nuclear Power Plant Accident (1986) and the Fukushima Daiichi Nuclear Power Plant Accident (2011) are the most known of these accidents. As the fallout of Chernobyl-derived ^{137}Cs affected a considerable part of Europe, this cesium (along with cesium of the global fallout) can be used as a chronomarker of recent processes of the accumulation of sediments eroded from soils [3, 27, 28]. However, the specific activity (concentration of the isotope) of Chernobyl-derived ^{137}Cs in soils of the EPR is characterized by a higher variability in comparison with that of the global fallout, which is related to the great spatial heterogeneity of the fallout with rains after the Chernobyl disaster. Within a larger part of European Russia, the peaks of maximum concentrations of ^{137}Cs isotopes of 1963 and 1986 are clearly identified in the uncultivated soils within the accumulative landscape positions with continuous input of soil particles, e.g., in dry valley bottoms, on floodplains, and in alluvial fans [6, 16, 18]. These peaks mark with sufficient accuracy (±1–2 cm) the position of the soil surface in the time of ^{137}Cs fallout in these years. Within landscape positions undisturbed by tillage or by other anthropogenic impacts and not subjected to erosion and sedimentation processes, the vertical distribution pattern of ^{137}Cs in the soil is characterized by a distinct peak in the uppermost 2–3 cm with a sharp decrease in ^{137}Cs concentrations in the underlying soil to the depth of 10–12 cm [30]. It should be noted that the accumulation of soil material in the accumulative landscape positions in 1954–1986 took place under relatively stable climatic conditions (up to 1976) and under the very beginning of the global warming stage (since 1976). The period of 1986–2016 was characterized not only by noticeable climatic changes but also by considerable changes in the character of land use after the breakdown of the Soviet Union in 1991.

The radiocesium technique has been widely applied to study the rates of erosional and accumulative processes in the EPR [7, 9, 11, 16, 23, 25, 26, 29, 32, 34]. However, it has not been used for assessing recent trends in degradation of arable soils.

SOIL AND CLIMATIC CONDITIONS OF THE STUDIED REGION

The studied territory is found on the eastern megaslope of the central part of the Central Russian Upland (Fig. 2). Relief of this area is characterized by a relatively deep (70–130 m) and dense (0.8–0.9 km/km^2) drainage network. The density of gully network in the Veduga River basin at the end of the 1990s averaged 0.5 km/km^2 [12, 17] reaching 1.1 km/km^2 in most dissected parts. The territory is composed of thick layers of the Upper Cretaceous (the Senomanian and Turonian stages) deposits represented by sands, marl, chalk, and siliceous sandstone overlain by the Paleogene and Neogene deposits represented by quartz–glauconite or quartz sands with thin clayey interlayers [10] exposed in some places in river valleys.

The major climatic characteristics affecting the development of surface runoff and soil erosion are precipitation during the cold and warm seasons and the depth of soil freezing, which is a limiting factor of surface runoff during the snowmelt season [22]. The mean annual precipitation (calculated for 1950–2013 according to weather records at Voronezh weather station) is 559 ± 27 mm, including 411 ± 23 mm (73.5%) of the warm season (April–November) and 148 ± 13 mm (26.5%) of the cold season (December–March). The maximum monthly precipitation is in June, and the minimum monthly precipitation is in February. The snow cover is established in December (in some years, as late as in January or even in February) and disappears by the end of March. In the recent decades, the rise in mean annual temperature (mainly, due to warmer winters) and precipitation has been observed (Table 2).

The major parent materials on the interfluves in the Veduga River basin are represented by covering and colluvial loesslike loams and by clays. Zonal soils of the interfluves are typical and leached chernozems (Haplic Chernozems (Pachic) (WRB)). In places of shallow embedding by eluvium of chalk rocks, they are replaced by calcareous chernozems (Calcaric Phaeozems) [2]. On steep slopes of river valleys, outcrops of the Turonian chalk are observed.

On the slopes of the studied catchment, clayey soils predominate. The soil cover of the cultivated part of the catchment can be judged from Fig. 3. The soil cover of gently slopes of the local flat-bottomed dry valley (balka) in its upper reaches consists of the same soils that occupy adjacent interfluves. Steep slopes of the balka in its middle and lower reaches are covered by weakly developed soils (Eutric Regosols Siltic Protocalcic) forming at the stage of leveling of balka slopes and their fixing by herbaceous vegetation. In the bottom of the balka, under conditions of regular input of new portions of sediments eroded from the upper relief positions, stratified soils (stratozems) or meadow-chernozemic soils (Stagnic Phaeozems (Colluvic, Pachic)) developing from alluvial–colluvial sediments are formed [8].

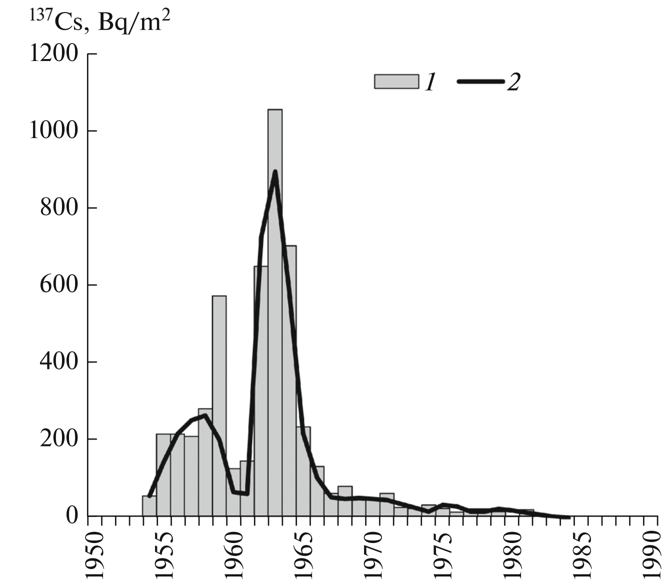

Fig. 1. Dynamics of the global ^{137}Cs fallout (of bomb origin) in the (*1*) northern hemisphere (according to generalized data [35]) and (*2*) Leningrad oblast of Russia (according to [21]).

The classification of specific soils of the bottoms of balkas and gullies is only developed in Russia. Thus, according to the new Russian soil classification system [14], the soils of the bottoms of the balkas adjacent to cultivated slopes are classified as dark-humus stratozems underlain by buried soils (Stagnic Phaeozems (Colluvic, Pachic)(WRB)). M.A. Glazovskaya [4, 5] suggests that such soil objects experiencing regular accumulation of sediments eroded from slopes of local catchments should be referred to as pedolithosediments.

In the studied area, a 10-field crop rotation is practiced: fallow—winter cereals—sugar beets, root vegetables—barley—corn—pees—winter cereals—sugar beets, corn—summer cereals—sunflower.

OBJECT AND METHODS

A first-order catchment in the basin of the Veduga River (right tributary of the Don River, F = 1570 km^2) was selected as the object for this study. Morphometric

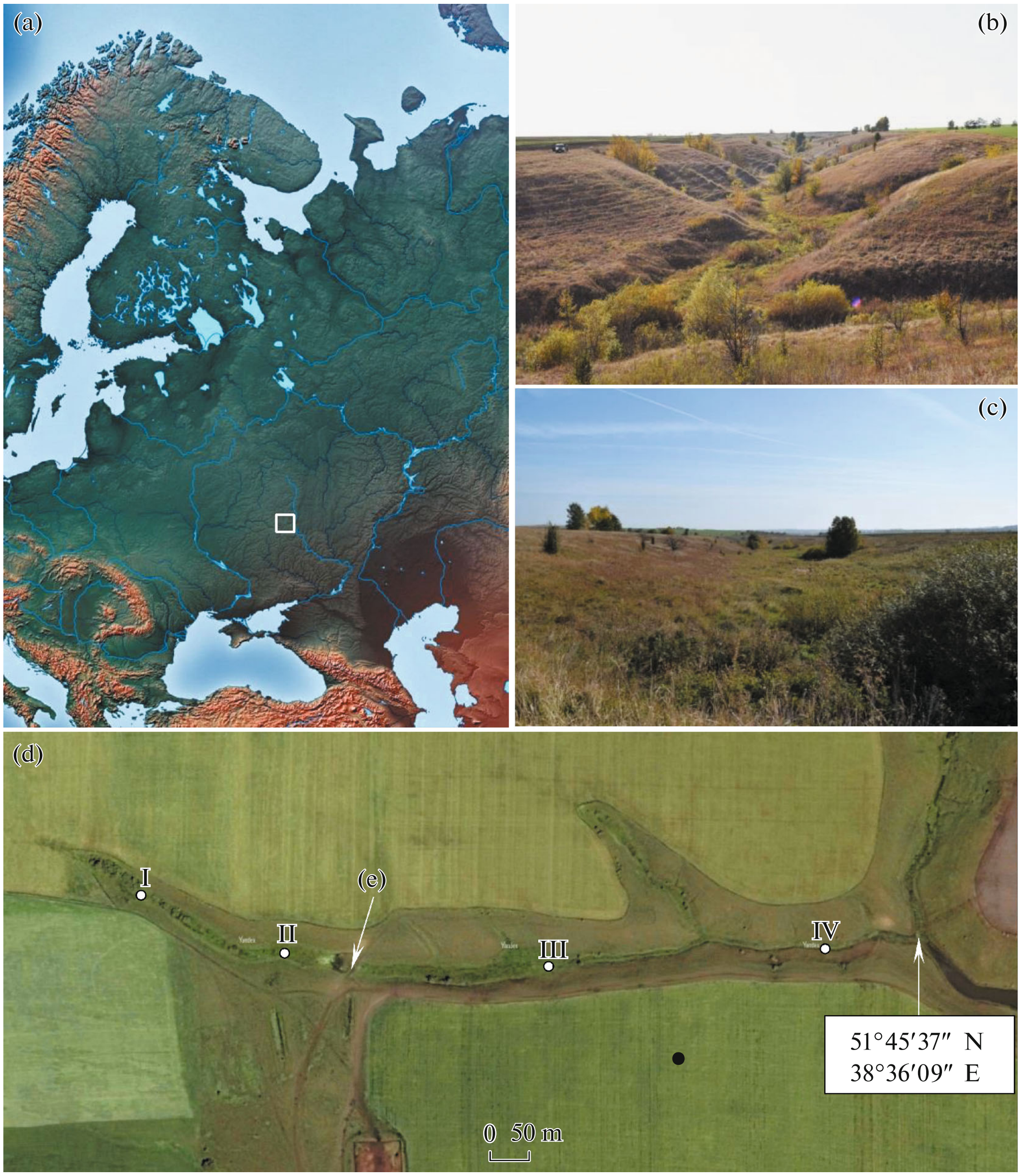

Fig. 2. (a) Location of the studied first-order dry valley in the European territory of Russia, general view of the valley in its (b) middle and (c) upper reaches, and (d) location of soil pits (I, II, III, and IV) along the valley bottom; (e) is the earth dam.

and soil characteristics of this catchment are typical of the Central chernozemic region (Fig. 2a).

The length of a small dry valley (balka), which is a part of a larger balka system, comprises 1183 m; together with initial hollow, 1463 m. The catchment area is 1.15 km^2; the area of the balka proper, 0.11 km^2; the area of its bottom, 0.02 km^2; and the average slope, 0.04. Average absolute height of the catchment is 177 m a.s.l.; the amplitude of heights reaches 43 m. The slopes of the catchment are entirely under cropland cultivated for at least 70 years. Arable fields are found above the balka brow; slopes and bottom of the balka are used as pastures (Fig. 2b). Since 1991, the grazing pressure has been considerably lower than in the previous years because of the reduction of livestock. An earth dam is present in the upper third of the balka (Fig. 2d). This dam is shown on the topographic map of 1988. Probably, it was constructed in 1970s. Sediments eroded in the upper part of the balka catchment are retained by this dam. Sediment transport to the bottom of the balka takes place along the upper hollow that begins within the plowland (Fig. 2c) and from both sides of the balka. In the period of fieldwork in summer 2015, no erosional cuts were noted along the thalweg of the hollow. In the place of transition from the hollow to the vegetated bottom of the balka

Table 2. Changes in the mean annual temperature and precipitation according to records of Voronezh weather station for 1950–2013

Characteristics	Observation period	Average values for observation periods	C_v^*
Temperature, °C			
Cold period (December–March)	1950–1964	–7.0 ± 1.4**	0.39
	1965–1983	–6.1 ± 1.0	0.37
	1984–2013	–4.7 ± 0.9	0.51
Warm period (April–November)	1950–1979	12.3 ± 0.4	0.08
	1980–2013	13.1 ± 0.4	0.09
Precipitation, mm			
Annual	1950–1979	534.2 ± 25.5	0.13
	1980–2013	595.2 ± 37.5	0.19
Cold period (December–March)	1950–1964	122.3 ± 17.9	0.29
	1965–1983	166.6 ± 27.3	0.37
	1984–2013	152.9 ± 15.4	0.28
Warm period (April–November)	1950–1979	389.2 ± 19.4	0.15
	1980–2013	440.8 ± 34.7	0.23

* Coefficient of interannual variability.
** Confidence intervals were determined for 95% probability level.

proper, a clearly pronounced alluvial fan with aggraded soils was observed. On the slopes of the balka, at the boundary between plowland and vegetated brows of the balka, plowed up artificial levees of up to 0.5 m in height prevent direct outflow of sediments from the plowland to the balka bottom. However, the capacity of these levees to stop sediment discharge is already exhausted, and soil material eroded from the plowland is directly transported towards the balka bottom. From the left side of the balka, additional input of sediments takes place along two short tributaries of the balka. At present, these tributaries are the areas of sedimentation. There are also two hollows with secondary erosional cuts in the middle part of the left slope of the balka. The cropland above the right side of the balka is found on relatively short and gentle slopes. The concentration of runoff does not take place within these slopes, which allows us to suppose that the rate of soil loss from this part of the balka catchment is relatively low.

The major task of the field study was to examine the sources of soil material eroded from the plowed fields to the balka bottom, to subdivide the balka into segments with different character of sediment redistribution, and to characterize accumulative (aggraded) soils forming within different parts of the balka bottom.

First, we examined the morphology of the balka to delineate the boundaries of its bottom and its slopes, to localize the positions of the sources and mouths of small branches on the left side of the balka, and to characterize vegetation conditions of the territory for phytoindication of the main ways of sediment transport and the areas of sedimentation. A laser rangefinder was used to measure the width of the bottom of the balka and the slopes of its sides. Morphometric characteristics (slope steepness, lengths of slopes, and width of the bottom) were measured along the entire length of the balka. A tacheometric survey with the use of a Leica Smart Station TPS 1200 tacheometer was applied. As a result, the morphodynamic scheme of the balka catchment was developed with indication of different elements of topography, the main routes of sediment transport from the slopes to the bottom of the balka, and segments of the balka bottom with different proportions between the accumulation and transportation of the sediments. In the latter case, the slope of the bottom of the balka and the presence of distinct channel in the bottom were taken into account.

This scheme was used to select soil sampling points. We examined four soil pits characterizing different parts of the balka bottom with respect to the intensity of sediment transportation/accumulation processes (Fig. 2d). Each of the pits was more than 1 m in depth, except for pit 3, where the shallow groundwater table made it possible its excavation to the depth of 0.6 m. The morphology of the corresponding soil profiles was thoroughly described. Layer-by-layer soil samples were taken from fixed area (15 × 15 cm to the depth of 0.5 m and 10 × 10 cm for the lower layers) for determining the specific activity of ^{137}Cs; the thickness of sampled layers was 2 cm down to the depth of 0.2 m, 3 cm at the depths of 0.2–0.5 m, and 5 cm at the depths of more than 0.5 m. Pit IV was found near the balka mouth, where the accumulated sediments have a considerable thickness. In this pit, samples were taken from each 3-cm-thick layer to the

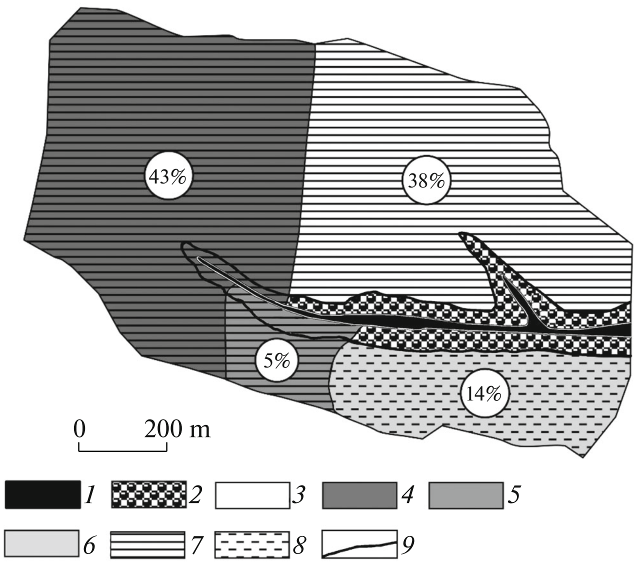

Fig. 3. Soil cover of the studied catchment (according to [2] with modification). Soils: (*1*) stratozems or meadow-chernozemic soils (Stagnic Phaeozems (Colluvic, Pachic)), (*2*) weakly developed primary soils (Eutric Regosols Siltic Protocalcic) of steep slopes of the valley, (*3*) medium-humus medium-deep leached chernozems (Luvic Chernozems), (*4*) medium-humus deep typical chernozems (Haplic Chernozems (Aric, Pachic)), (*5*) low-humus medium-deep typical chernozems (Haplic Chernozems (Aric, Pachic)), and (*6*) low-humus slightly eroded typical chernozems (Haplic Chernozems (Aric)); soil texture: (*7*) clayey and (*8*) heavy loamy; (9) brow of the dry valley.

depth of 0.6 m (from the area 15 × 15 cm) and from each 5-cm-thick layer (10 × 10 cm) in the deeper horizons.

The specific activity of ^{137}Cs in the soil samples was determined in laboratory. The samples were dried at 105°C, ground, and sieved through a 1-mm sieve. The specific ^{137}Cs activity was measured on a coaxial germanium γ-spectrometer with a relative error of up to 10%. The pretreatment of the samples and spectrometric measurements were made in the Laboratory Center of the Geographical Faculty of the Lomonosov Moscow State University. The obtained data were used to construct the curves of the vertical distribution of ^{137}Cs in the soil profiles. In each of them, there were peaks of the specific activity of ^{137}Cs related to Chernobyl-derived fallout. The position of these peaks in the soil profiles characterized the position of the soil surface in 1986.

Morphometric characteristics of the balka and the curves of the distribution of ^{137}Cs in the vertical soil profiles (Fig. 4) were used to calculate the volumes of soil material accumulated at the bottom of the balka in two periods: 1954–1986 and 1986–2015. The volumes of the accumulated material were determined via calculation of the areas of trapezoids on the plots with examined cross-sections of the balka. The upper trapezoid (characterizing sedimentation in 1986–2015) was bordered by the width of the balka bottom at the soil surface (upper side) and its width at the depth of the maximum concentration of cesium corresponding to 1986 (lower side). In all the pits, the peaks of ^{137}Cs of the Chernobyl origin are clearly identified. Taking into account the fact that the vertical migration of ^{137}Cs in undisturbed soils of the forest-steppe zone is about 12–15 cm [13, 18, 29, 32], and the peak of ^{137}Cs concentration deepens down by no more than 1–2 cm, the total pool of ^{137}Cs in the layer with its maximum concentration and in the underlying 12–15 cm is equal to the initial ^{137}Cs fallout in April and May 1986. After the recalculation with due account for the ^{137}Cs half-life, the density of the soil contamination in this layer in pits I, II, III, and IV comprised 13.4–17.8, 14.6–21.4, 17.8–21.0, and 5.2–20.6 kBq/m^2, respectively, which is in agreement with data on the density of radioactive contamination of this part of Voronezh oblast shown in the Atlas of radioactive contamination of the EPR, Belarus, and Ukraine [3]. The lower trapezoid (the layer contaminated in 1954–1986) was bordered by the width of the balka at the depth of the maximum concentration of ^{137}Cs corresponding to 1986 (upper side) and its width at the lower sampling depth for which the concentrations of ^{137}Cs were determined (lower side); it was conventionally taken as the layer corresponding to the beginning of ^{137}Cs fallout in 1954. The peaks corresponding to 1963 could not be clearly distinguished in the studied soil profiles. Moreover, we failed to reach the lower layers, in which ^{137}Cs was reliably absent. This means that we cannot exactly determine the total thickness of sediments deposited in 1954–1986. Taking into account the vertical migration of ^{137}Cs, the position of the boundary corresponding to 1954 can only be established with an accuracy of no more than ±5–6 cm. At the same time, the presence of ^{37}Cs in significant concentrations (3–6 Bq/kg) makes it possible to estimate the minimum thickness of sediments accumulated in 1954–1986 with an accuracy of ±5–6 cm. In this estimate, the maximum depth, at which the presence of ^{137}Cs of the global fallout was identified, and the vertical migration of ^{137}Cs of the global fallout to a distance of 10–12 cm were taken into account. This assumption somewhat decreases the accuracy of determination of the volumes of sediments accumulated in 1954–1986.

The lateral sides of the trapezoids corresponded to the slopes of the balka sides at the given cross-sections. The distance between these cross-sections was measured along the lengthwise profile of the balka bottom. Volumetric estimates of sedimentation were converted into sediment weight via multiplying them by the average bulk density of the soil samples.

Weather records of Voronezh and Staryi Oskol weather stations for the period from 1950 to 2013 were obtained from the open-access internet resource supported by the All-Russia Research Institute of Hydrometeorological Information–World Data Centre (RIHMI-WDC) [www.meteo.ru].

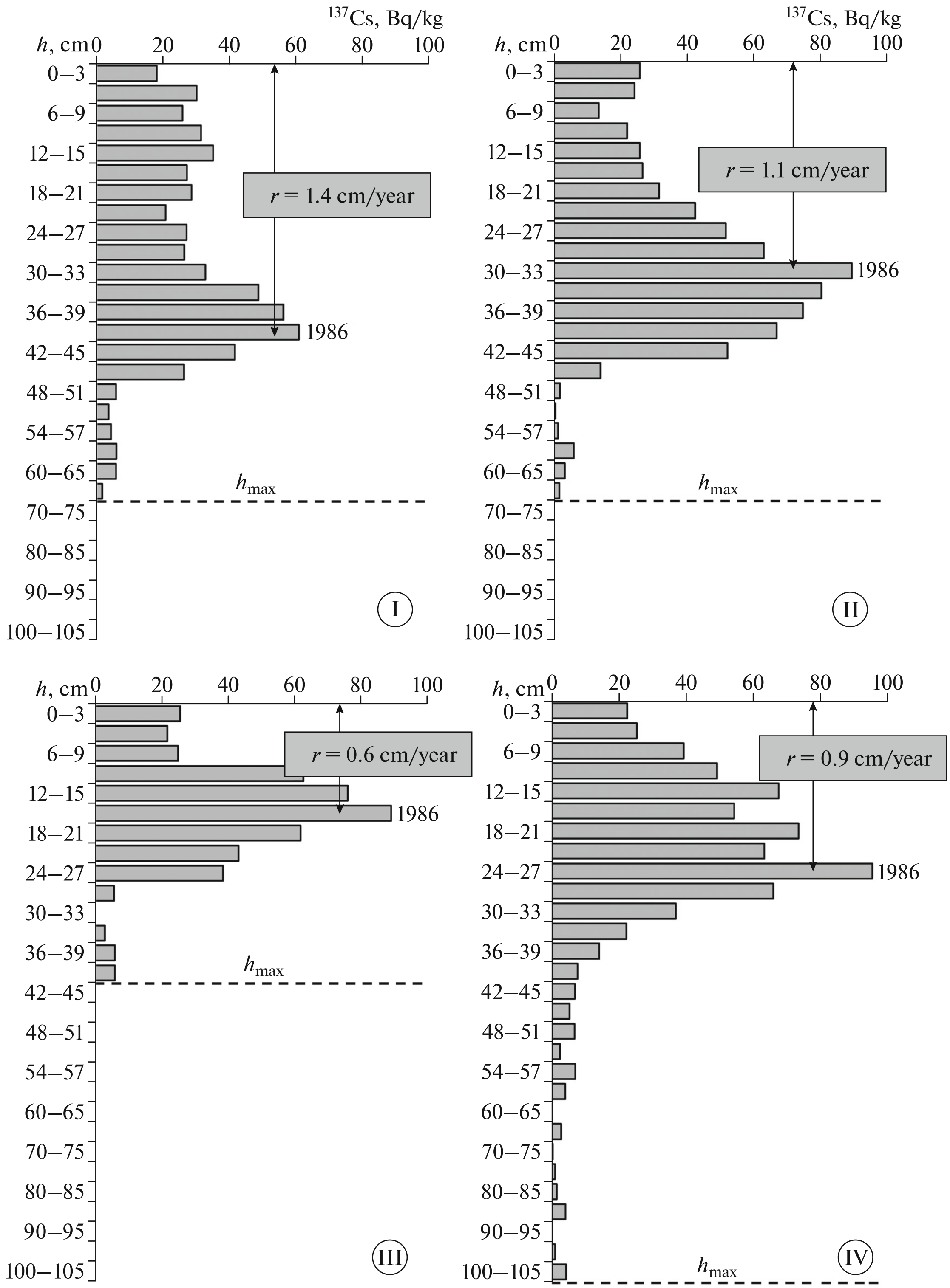

Fig. 4. Vertical distribution of specific activity of ^{137}Cs in the soil profiles under study. Here and in Fig. 5: (I, II, III, and IV)—pit numbers; h—sampling depth (h_{max}—maximum depth); r—mean annual rate of sedimentation since 1986.

RESULTS AND DISCUSSION

Under conditions of considerable contrasts in the color and texture of genetic horizons of the cultivated soils, the pits displaying the morphology of sediments accumulated at the bottom of the balka owing to the redeposition of the material eroded from the adjacent fields are highly informative. The analysis of the descriptions of the soil profiles allows to attribute certain layers of the redeposited material to the particular genetic horizons of the soils plowed on the slopes and, hence, to determine the type of erosional processes responsible for the loss of sediments from the slopes and their transportation to the balka bottom. In all the four studied pits, the layered character of the sediments is clearly pronounced. Each layer is specified by the given event of sediment redeposition. It is possible to subdivide the entire thickness of accumulated sediments into several layers differing in their color, density, texture, pedofeatures, and (in some cases) included artifacts. The thickness of the layers deposited during the given events varies from 1–2 to 12–15 cm. The position of these layers in sediment columns dated with the help of ^{137}Cs chronomarker in different parts of the balka bottom is important. Its analysis makes it possible to conclude about the spatiotemporal dynamics of the soil cover degradation within the studied catchment. Let us analyze our data on the soil profiles (sediment columns) in different parts of the balka bottom from the upper to the lower reaches.

Pit I is found in the upper part of the balka bottom. The profile consists of alternating layers of humified material, interlayers and lenses of silty material, and distinct bright brown clay loamy material (derived from the B horizon of the soils on the slope). The inverse color pattern of the layers of humified materials should be noted: in the upper 50–60 cm, these layers are brownish gray; in the deeper part, they are dark gray or almost black. This attests to the fact that the degree of erosion of the cultivated soils on the interfluve has been increasing continuously. Unstable fine crumb structure of the upper 20 cm attests to the relatively recent deposition of the material that remains poorly transformed by pedogenesis at the balka bottom. The underlying sediment layers of an older age have a perfect granular–crumb structure. A very specific angular structure with sharp edges in the layer of 22–54 cm may be indicative of the multiple changes in the moisture regime of this soil with the periods of relatively long water stagnation. At the depths of 54(57)–90(91) and 90(91)–94 cm, there are numerous discontinuous interlayers of the bright brown heavy loam. It is probable that this material was derived from deep erosional rills dissecting the soil of arable fields down to the depth of the illuvial horizon. This material could also be derived from the slopes of the hollow leading to the head of the balka. The angular blocky structure of the brown material resembles the structure of the B horizon of the initial soils and points to relatively short distances of sediment transport. The analysis of specific activity of ^{137}Cs in the collected samples shows that the concentration of this isotope sharply decreases from 6 to 1.9 Bq/kg in the layer of 65–70 cm. This confirms the deposition of sediments eroded from the deep soil horizons (initially not exposed to the radioactive contamination) in this layer. The Chernobyl-derived peak of ^{137}Cs concentrations with the specific activity of about 60 Bq/kg in pit I is observed at the depth of 39–42 cm. The analysis of the morphology of the sediment column in this indicates that it has not been subjected to rill erosion since 1986. In the post-Chernobyl period, this part of the balka bottom has been the area of the predominant accumulation of sediments.

Pit II is found in the upper part of the dried former pond filled with sediments that were retained in this place by the earth dam. The supposed thickness of sediments accumulated near the dam is no more than 1.5 m; the depth of the pit was 107 cm. The soil is composed of the sediments eroded from the upper soil horizons. The inclusions of small debris of chalk in the layer of 2–43 cm may be related to the zoogenic turbation by the earthworms. Chalk debris (up to 0.5 cm in diameter) in the layer of 43–83 cm attest to active erosion upstream of this soil pit. The inversion of color (dark gray color with brown tint in the upper horizons and dark gray to black color in the lower horizons attests to a consecutive increase in the degree of soil erosion on the interfluves during the period of the pond existence. The Chernobyl-derived peak of ^{137}Cs (90 Bq/kg) is seen in the layer of 30–33 cm. The lower sediment layers were accumulated in 1954–1986. The absence of soil samples for the radioisotopic analysis from the depth of more than 70 cm does not allow to date the lower layers (down to 80 cm) more reliably.

Pit III is found on the bottom of the dry valley downstream the earth dam and the upper left branch of the balka. In this area, the bottom is virtually flat and contains a secondary erosional cut with ponded water in some microlows. In the soil pit, water appeared at the depth of 32 cm; the water table was established at the depth of 58 cm. The soil is composed of humified sediments with wavy interlayers of silty material in the upper 10–12 cm. The Chernobyl-derived peat of ^{137}Cs (90 Bq/kg) is found at the depth of 15 cm. This sediment layer is entirely composed of the humified material from the humus horizons of the soils on the interfluve slopes to the balka. In the lower sediment thickness, a discontinuous interlayer of bright brown heavy loam derived from the illuvial soil horizons is traced at the depth of 33 cm. In this particular material (30–33 cm), the concentration of ^{137}Cs tends to zero. Thus, in the area of pit III, as well as in the pits upstream, the deposition of sediments eroded from the deep soil horizons on the interfluve along the rills took place in the period from 1954 to 1986. A relatively low thickness of the accumulated sediments and the flat bottom of the balka with a narrow erosional cut allow to consider this position as the position of predominant transition of transported sediments without their considerable accumulation.

Pit IV is found in the central part of the bottom of the dry valley downstream the confluence of the second left branch of the balka. The bottom is slightly convex in its cross-sectional profile; the thalweg zone is not pronounced, and there are no secondary ero-

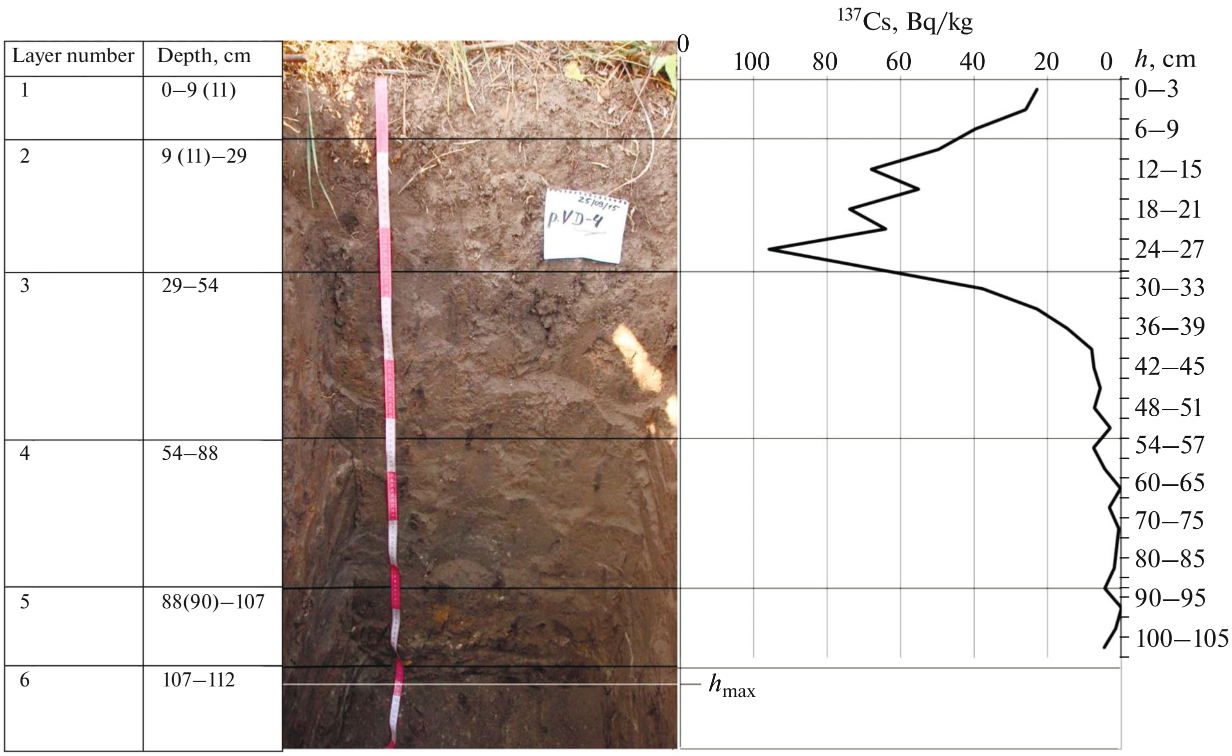

Fig. 5. Soil profile in pit IV and vertical distribution of specific activity of ^{137}Cs in it.

sional cuts. The surface is overgrown by ruderal plants with some participation of native herbs and sparse willow shrubs. The sampling was performed in September 2015, after the summer discharge of considerable volumes of water, as indicated by the dry stems of corn and tall weeds oriented along the axis of the balka. These plant residues accumulated in front of willow shrubs that served as barriers for water flows carrying them. The surface horizons are composed of recently deposited sediment layers of about 10 cm in thickness with inclusions of sod fragments in the lower part (Fig. 5). The underlying sediment thickness is heterogeneous and consists of the material from the topsoil horizons and from the deep soil horizons subjected to erosion along the rills and growing gullies. A comparative analysis of the morphology of this soil profile and ^{137}Cs distribution data allows us to suppose that the upper layers of the sediments accumulated since 1986 are mainly the products of sheet erosion on the interfluves. The Chernobyl-derived peak was found at the depth of 24–27 cm. In the deeper layers, there are abundant fragments of bright brown heavy loam, sandstone and chalk debris, and interlayers of quartz sand. In these materials, the ^{137}Cs concentration is very low. Such sediments could be eroded from the deep soil horizons on the interfluves owing to the development of linear erosion. In particular, the layer of 90–95 cm is characterized by the absence of ^{137}Cs; it represents a strongly effervescent heavy loam enriched in fine chalk debris. It is interesting that such layers alternate with the layers containing ^{137}Cs down to the depth of 105 cm. Thus, we can suppose that the thickness of sediments accumulated in 1954–1986 in this particular place is no less than 81 cm. It is also probable that the peak in ^{137}Cs concentration of 1963 disappeared from this soil owing to erosion, so that the observed thickness of sediments was shaped after 1963.

A combined analysis of the curves of the vertical distribution of ^{137}Cs and data on the morphology of soil-sedimentary sequences in the pits under study allows us to conclude about the direction of erosional and accumulative processes with in the catchment and at the balka bottom. Thus, in all the pits, the peaks of ^{137}Cs concentration corresponding to the Chernobyl-derived fallout in April–May 1986 are clearly seen (Fig. 4). From the first to the third pit, the thickness of sediments deposited after 1986 tends to decrease from 39–42 to 15–18 cm; in pit. IV, this layer of sediments becomes thicker again.

All the samples from the accumulated sediments of 40 to 105 cm in thickness for different parts of the bottom contain ^{137}Cs. In all the pits, sediment layers located above the horizon with the maximum ^{137}Cs concentration (corresponding to Chernobyl fallout) are composed of the material from the upper (humus) soil horizons subjected to sheet erosion. Thus, since 1986, no new forms of linear erosion have appeared on the interfluves. Rill erosion was atypical for this period. In the layers below the layer with the maximum ^{137}Cs concentration, there are interlayers of bright brown heavy loam that could only be derived from the deep (illuvial) soil horizons on the interfluves subjected to rill and gully erosion. Such interlayers are characterized by the very low concentrations of ^{137}Cs. Thus, they represent the material eroded from the deep soil horizons on the interfluves, on the balka slopes, and in the balka bottom. Such horizons in their initial position could not be affected by the Chernobyl fallout, because the maximum depth of the ^{137}Cs migration in soil profiles upon the soil tillage, illuviation of clay particles, and bioturbation is no more than 10–12 cm below the lower boundary of the plow layer. Thus, the material found at the depth of 30–35 cm could not contain Chernobyl-derived ^{137}Cs. The development of gully erosion on the slopes of the balka could also be accompanied by the partial erosion of underlying bedrock, which is seen from the presence of chalk debris in pits II and IV.

Unfortunately, the peaks corresponding to maximums of global fallout (1963) have not been identified in the studied pits. The layers with such peaks could be eroded afterwards. In pits I and II in the upper part of the balka, the sampling depth could be insufficient to reach the layers with this peak. This allows to state that the balka bottom (at least, its lower part) in the 1960s was the area of the predominant loss (erosion) of the sediments. Later, the situation changed. A gradual filling of the valley draining this balka with sediments resulted in the substitution of accumulative processes for erosional processes in the balka. However, even if we do not take into account sediments discharged through the balka, the amount of sediments accumulated in the balka is very significant. For 1954–1986, it comprised no less than 8000 t, or 259 t/yr. For 1986–2015, it comprised 3600 t, or 120 t/yr. Since 1986, accumulative processes predominated over erosional processes in the bottom of the balka. Taking these acts into account, we come to conclusion that the rate of soil loss from arable fields of the catchment decreased by at least two times in comparison with that during the previous period. The factual decrease of the soil loss from the cultivated slopes could be even more significant, because the absence of the peaks of ^{137}Cs corresponding to 1963 in the pits under study (at least, in the pits characterizing the lower part of the balka) indicates that the outflow of sediment material from the balka predominated over sedimentation in the balka in the period from 1954 to the mid-1960s.

The construction of the earth dam in the central part of the balka in the 1970s resulted in the retention of a larger part of the sediments eroded from the arable fields. Upstream this dam, 3140 t of sediments removed from the balka catchment have been accumulated. In the period of 1986–2015, virtually all the material removed from the catchment upstream was retained by this dam. Its amount is estimated at 1220 t. This means, that the rate of soil loss from the arable fields in this period averaged 0.91 t/ha per year, which is in agreement with data on the soil loss for other soils in the southwestern part of the forest-steppe zone for the given time period [7]. In the period from 1954 to 1986, the amount of sediments accumulated on the bottom upstream the dam was at least 1910 t (1.38 t/ha per year). Note that before the dam construction (in the 1970s), a larger part of the soil material was transported by flows through the balka towards its lower reaches.

The major part of sediments accumulated on the balka bottom is derived from arable fields owing to sheet and rill erosion. Additional portions of material could be due to the erosion of deep soil horizons in the growing left branches of the balka. They were mainly formed before 1986 as judged from the composition of sediments accumulated in the lower part of the balka bottom. Some part of sediments could be derived due to erosion of steep slopes of the balka in its lower reaches (also before 1986). In the recent decades, the contribution of gully erosion to the sediments accumulated on the balka bottom has been minimal. The major part of these sediments was eroded from the plowed fields by sheet erosion processes.

We suppose that the major reason for sharp differences in the intensity of erosion/sedimentation processes is related to changes in the hydrometeorological conditions in the region. In the past 50 years, a steady tendency for the rise in winter air temperatures has been observed; the snowmelt season shifts toward earlier days. A general warming of the climate, especially in the winter months, leads to a reduction of the reserves of water accumulated in the snow and to a shallower depth of the soil freezing, which is especially important for the snowmelt runoff formation (Fig. 6). As a result, the snowmelt runoff and, hence, soil erosion have become less pronounced. The erosion of steep balka slopes by runoff flows has also been attenuated. Since 1986, it only takes place in some years. The described tendency of climatic changes has a regional character [33]. According to [1], river discharges in the neighboring Kursk oblast have decreased by 15–25% on the average, and the decrease in the spring runoff layer comprised 4–10%. Maximum water discharge during spring floods has reduced considerably. A decrease in the coefficients of runoff flows from plowed fields was proved for test plots of the Novosil'skaya zonal agroforest reclamation station (150 km to the north of the studied object) [20]. A general consequence of these changes is the decrease of soil loss from the interfluves and sedimentation on the floodplains of local rivers [16].

Certain changes in the frequency of rainstorms have taken place during the warm season, For rains with the layer of 10–30 mm, no clear tendency of changes in their frequency was observed in 1963–2015 (Fig. 7). However, heavy rains with precipitation layer

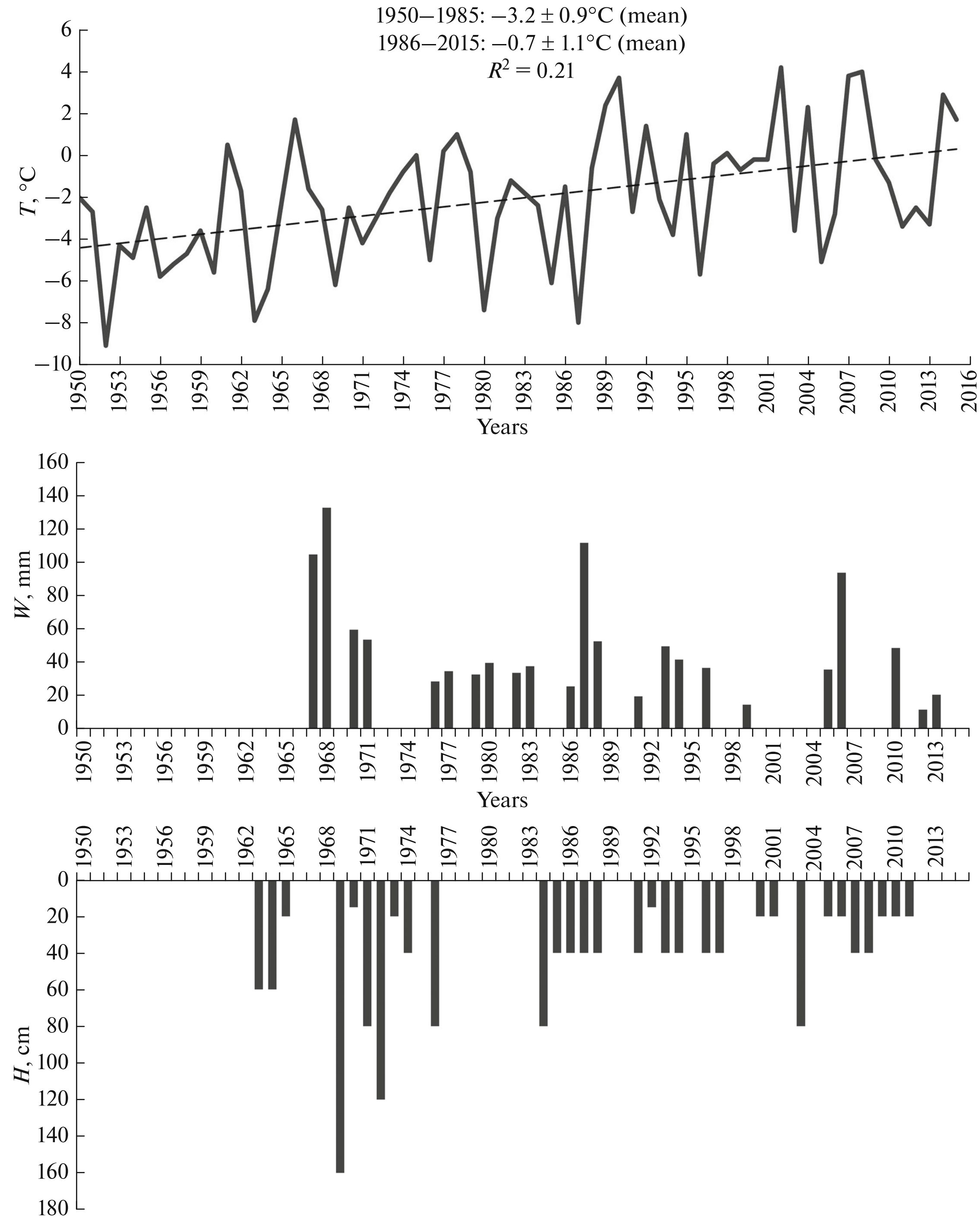

Fig. 6. Changes in the mean monthly air temperature in March (*T*) (Voronezh weather station), water reserves in the snow (*W*, March 15), and average soil freezing depth (*H*, first half of March) (Staryi Oskol weather station) in 1950–2016; zero values of water reserves in the snow and soil freezing depth indicate the absence of information for these particular years.

of more than 30 mm, which have the greatest erosive potential, display a tendency for some increase in their frequency since the 1980s. Thus, according to records at Voronezh weather station, in the period of 1986–2013, there were 11 rainstorms with the precipitation layer of 40–50 mm; this is almost 3.5 times higher than the number of such rainstorms in 1950–1975. Rainstorms with precipitation layers of 30–40 and >50 mm also tend to become more frequent (Fig. 7). However, such rainstorms mainly take place in summer months (64% of rainstorms with precipitation layer of 40–50 mm and 89% of rainstorms with pre-

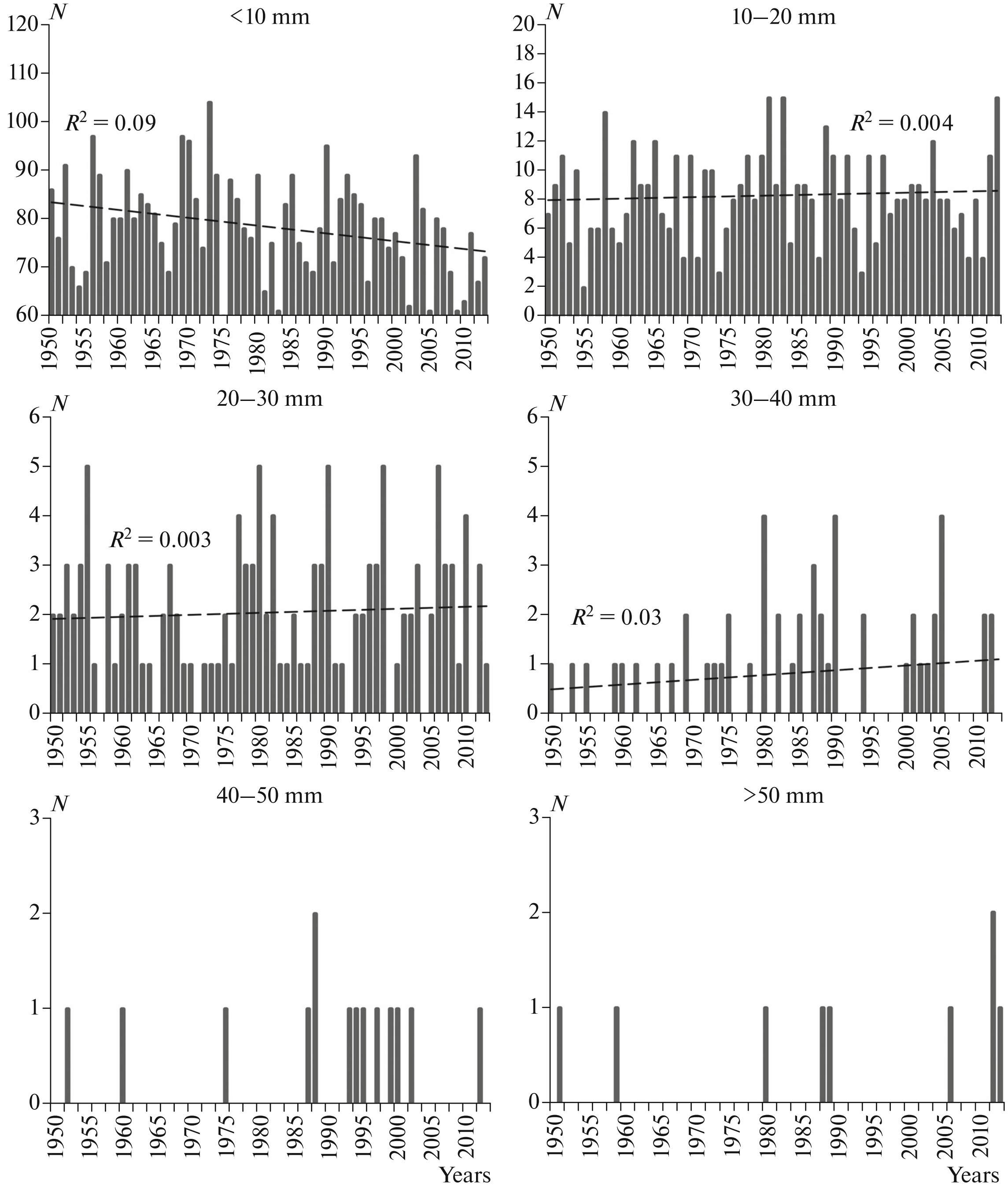

Fig. 7. Changes in the number of days with rainfall events (*N*) with different precipitation layers during the warm season (April–November) according to records at Voronezh weather station in 1950–2013. Number of days with different precipitation layers, days/yr:

Precipitation layer, mm	1950–1979	1980–2013
<10	81.5	75.8
10–20	7.9	8.7
20–30	1.9	2.2
30–40	0.5	1.1
40–50	0.1	0.3
>50	0.1	0.2

cipitation layer of >50 mm), when the soil-protective coefficient of crops (C) is higher ($C = 0.29–0.45$) than that in the spring ($C = 0.66–0.67$). During the snowmelt runoff in March, $C = 0.88$, which means that the soil is poorly protected from erosion. Hence, we can assume that the effect of the increasing number of heavy rainstorms (precipitation >30 mm) in summers of the recent decades (since 1986) on the rates of soil loss from the catchment has not been significant. The zones of sedimentation on the bottom of the balka and its tributaries (branches) could be seen during the survey. These sediments were eroded during the strong rainstorm in the previous (2014) year. The zones of their accumulation could be delineated using phytoindication method: they were characterized by the bright green herbaceous vegetation with abundant ruderal species and with some growths of crops (in September 2015, sunflower), the seeds of which were delivered to the balka together with sediments eroded from the tilled slopes.

For the catchment under study, no radical changes in the character of crop rotation and in the area under cultivation have taken place since 1986.

CONCLUSIONS

A new approach toward quantitative assessment of changes in the rates of degradation of arable soils on the basis of data on the rates of sedimentation (the rate of formation of specific stratified soils, stratozems) in the bottoms of small first-order dry valleys adjacent to arable fields is suggested. This approach is applicable for small catchments with the high percent of arable soils subjected to moderate and weak radioactive contamination with ^{137}Cs after the Chernobyl Nuclear Power Plant accident.

The approach has been tested on a small catchment in the Venduga River basin in the west of Voronezh oblast. Data on the rates of the development of stratozems in different parts of the studied dry valley bottom indicate that the period of 1986–2015 was characterized by at least the twofold decrease in the intensity of erosion of arable soils in comparison with that in 1954–1986. This means that the average rate of degradation of plowed soils has also decreased.

The reason for this may be associated with a decrease in the snowmelt runoff in spring because of the general warming of the climate and, especially, warmer winter seasons, the decrease in the depth of soil freezing, and the decrease in the pool of water accumulated in the snow by the beginning of the snowmelt season. The higher projective cover of crops in the summer has mitigated the effect of heavy summer rains (>30 mm) that have become more frequent in the recent 25 years.

The changes in crop rotation and in the area under cultivation within the test catchment have been insignificant since the 1950s and have not affected the observed tendency for the decrease in the rate of soil degradation. Taking into account the major role of the climate in the observed changes in the rates of soil degradation (erosional and accumulative processes), we can extrapolate the obtained conclusions over the entire southwestern sector of the forest-steppe zone of European Russia.

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