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Combining direct observations, modelling, and ^{137}Cs tracer for evaluating individual event contribution to long-term sediment budgets

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Abstract The contribution of individual extreme events to longer-term sediment budgets is difficult to evaluate without continuous records of precipitation, runoff, and sediment yield for a particular catchment. This imposes certain restrictions on the applicability of average soil redistribution rates obtained using the most widespread integrative approaches. The problem may partly be resolved by direct observations immediately after extreme runoff events, when their effects are still prominent. We attempted to combine such direct measurements of event erosion and deposition volumes with longer-term soil redistribution rates obtained by ^{137}Cs tracer and empirical erosion models. Available meteorological data were obtained from official sources to evaluate recurrence periods of the observed events. Additional information obtained by other independent techniques, such as the soil profile comparison method, was also considered. Such a combination provides valuable information on the temporal variability of soil redistribution rates and the contribution of extreme events to long-term sediment budgets for the studied catchments.

Key words soil erosion; direct measurements of erosion and deposition; ^{137}Cs tracer; sediment redistribution

INTRODUCTION

The majority of field-based techniques, such as the ^{137}Cs radioactive tracer or soil profile comparison methods, provide information about average soil redistribution rates over more or less prolonged periods of time (Owens *et al.*, 1997; Belyaev *et al.*, 2005, 2007, etc.). Similar restrictions can be applied to most of the existing soil redistribution computational models (Van Rompaey *et al.*, 2001). Although many of those are claimed to be able to work at a single event scale, problems of detailed input data availability, such as precipitation, soil properties, crop rotations, etc., limit their applicability at such a detailed timescale. Reliable information on the contribution of high-magnitude, low-frequency events can only be obtained by continuous direct monitoring of precipitation, runoff and sediment yield from arable slopes, which is difficult to organize in natural conditions and is therefore in most cases limited to the erosion plot scale. On the other hand, it is well known that in most environments soil redistribution on cultivated land is mainly associated with relatively rare high-magnitude runoff events caused by extreme rainstorms. The discrepancy between the temporal resolution of available measuring techniques and the timescales of the relevant process behaviour imposes restrictions on the applicability of long-term average soil redistribution rates for development of soil conservation measures. It is believed that one of the possible approaches to resolve the problem is to obtain direct observations of soil redistribution on cultivated fields immediately after extreme runoff events, when their effects are still prominent. In this study we have attempted to combine direct measurements of erosion and deposition volumes with longer-term average soil redistribution rates obtained from application of the ^{137}Cs tracer technique and empirical erosion models.

CHARACTERISTICS OF THE STUDY SITES

This complex approach has been applied to three study sites in central European Russia (the Central Russian Upland) where runoff events occurring during our fieldwork periods over the last few years caused substantial sediment redistribution. All the three study sites are located within the Central Russian Upland (Fig. 1(a)) – a territory characterized by the highest topographic

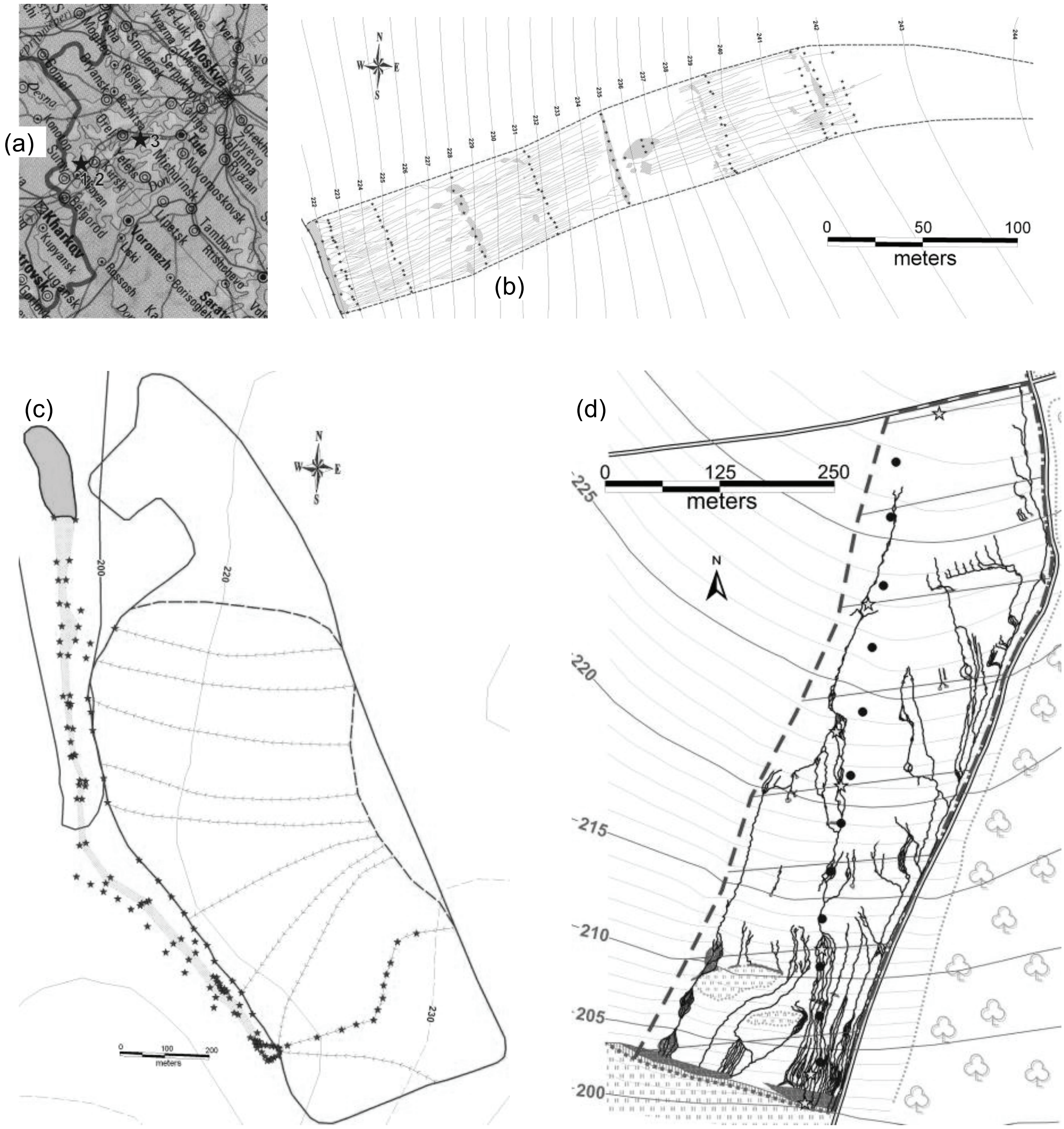

Fig. 1 (a) Location of the study sites within European Russia; (b)–(d) schemes of the study sites 1–3, respectively. Rill network and deposition features surveyed are shown in (b) and (d). Filled areas on (c) designate deposition area in the dry valley bottom (light grey) and reservoir (dark grey). Dashed lines show selected subcatchment boundaries. Stars on (b) and (c) designate measurement points. Stars and circles on (d) show ^{137}Cs sampling locations. Topographic contour lines intervals are 1 m on (b) and (d), 20 m on (c).

ranges, the largest percentages of cultivated areas and, consequently, the highest rates of human-accelerated erosion in European Russia (Litvin *et al.*, 2003).

The study sites 1 and 2 are located in the Kursk Region, approx. 20 and 10 km to the south of Kursk City. Soil cover of the area is characterized by leached chernozems on loessy loams. On study site 1 (Fig. 1(b)), an arable field occupies convex divergent slopes of northwestern aspect with maximum topography range about 25 m, length 400–600 m and gradients from 1° to 3–5°. The total area is about 30 ha, of which a 2.05 ha subcatchment was selected for detailed measurements. Available meteorological data suggest that an erosion event occurred on the 8–12 August 2006, associated with a moderate rainstorm (about 20 mm) falling on a recently harrowed fallow surface.

The study site 2 (Fig. 1(c)) was affected by an observed 40 mm rainfall event with relatively high intensity (about 30 mm within 0.5 hour) falling on the recently harrowed fallow surface on 14 August 2007 (Fig. 2). The arable field occupies convex slopes with generally western aspects and a complex transverse profile represented by a combination of divergent and convergent segments (Figs 1(c), 2). The cultivated slope length, maximum topography range and gradients are all similar to study site 1. Total area of the arable parcel is about 70 ha, of which a 60-ha subcatchment having topographic connection with the adjacent dry valley was used for detailed investigations (Fig. 1(c)).

Fig. 2 Convergent and divergent flow patterns on the case study field 2 immediately after cessation of the 14 August 2007 rainstorm. Photo taken from about 600–700 m distance. Note that absolutely no runoff is observed on the roughly ploughed arable field in the foreground. Photo by M. V. Markelov.

Study site 3 (Fig. 1(d)) is located in the Orel Region, approx. 20 km to the west of Novosil City, about 150 km north from study sites 1 and 2. Soil cover of the area is characterized by grey forest soils on loessy loams. The arable field occupies convex slopes with southern aspect and generally divergent transverse profiles (Fig. 1(d)). The slope length is 800–850 m, topographic range 35 m, gradients increase from 1° to 3–4°. Uncultivated spots in the lower parts of slopes represent remnants of the stone foundations of churches of a former village (Fig. 1(d)). The total area of the subcatchment studied is 15.4 ha. A rainfall event that caused measured erosion and deposition features on the studied slope took place on 11 August 2003, when the field was under fallow and recently harrowed. According to direct observation (about 1.5 km from the study site), the rainfall intensity slightly exceeded 20 mm in less than 1 hour.

METHODS

The main method used in this study has been direct measurements of erosion and deposition forms observed at the studied fields after the rainstorm events. Depending on the actual situation, two different measurement approaches have been applied. At the study sites 1 and 3, where rainstorm intensities and associated soil redistribution were relatively moderate, detailed measurements of all erosion and deposition forms were carried out along transects perpendicular to the main direction of slope gradient, more or less regularly spaced along the slope (Fig. 1(b), (d)). A different approach was used at study site 2, where erosion was visually more severe and in lower slope parts adjacent rills coalesced together, creating an impression of deep sheet wash. Therefore, it was difficult to distinguish the boundaries of erosional features. In addition, it was decided to attempt to acquire information on erosion over the larger area representing most of the entire cultivated parcel (area 60 ha). Therefore, our activities concentrated on detailed measurements of deposition volumes in the dry valley bottom and along its upper breaks below and above the plough terrace limiting the arable field lower boundary. It was decided to consider the total amount of sediment deposited in those locations as a reliable measure of erosion from the entire area of arable slope connected, as no noticeable depositional features have been observed within the cultivated area itself.

The empirical erosion model used to obtain the potential average annual soil loss rates for each of the studied fields utilizes a combination of the USLE-based approach for estimating rainfall erosion and a model developed in the Russian State Hydrological Institute for estimating erosion from snowmelt runoff (Larionov, 1993; Belyaev *et al*, 2007).

Inventories of ^{137}Cs in soil samples were measured at study site 3 in order to obtain independent information on soil erosion rates. Two sampling programs have been carried out to obtain not only average annual soil redistribution rates, as commonly achieved by the ^{137}Cs technique (Walling & Quine, 1990; Loughran, 1994, etc.), but also some independent quantitative evaluation of soil redistribution over the individual event observed. In order to achieve that, in August 2003, we took three individual integral samples by cylindrical steel corer to the depth of 30 cm (average plough depth 25 cm) at seven locations along the main rill system (designated by white stars on Fig. 1(d)) from three types of the eroded field surface microtopography: main rill bottom, visually eroded harrowing furrows, and visually uneroded harrowing ridges. All the three individual samples at a particular sampling point were located within a few metres of each other. In addition, samples for determination of ^{137}Cs concentration were taken from three depositional bodies (two within the slope and one from one of the main fans at the field's lower southern corner) in order to compare the isotope concentration in sediment with those in the plough layer and to evaluate the possible influence of grain-size selectivity of the sediment redistribution process. To check the validity of results obtained from this sampling program, we carried out normal integral sampling along the slope transect a year later (designated by black circles on Fig. 1(d)), when the field surface had become relatively smooth after cultivation and harvesting operations.

RESULTS

Study site 1

Regarding sediment redistribution during the individual rainstorm event, it must be noted that despite its relatively moderate magnitude (about 20 mm, according to the available meteorological record) very significant erosion took place on the field (Table 1). The sediment delivery ratio (SDR) into the adjacent dry valley was estimated as 49% for this event. Total deposition above the

Table 1 Results of direct measurement of erosion and deposition at the study field 1 compared with average annual soil loss rate calculated by the erosion model. Bulk density of recently harrowed topsoil layer was estimated as 1000 kg/m^3, and bulk density of freshly deposited sediment as 1300 kg/m^3, based on sample analysis.

	Directly measured after individual event:					Average annual soil loss rate calculated by the model (t/ha/year)
	Erosion	Deposition			Resulting soil loss from the field	
		Within the field	Along the lower field boundary	Total deposition		
Volume (m^3)	150.3	36.0	22.8	58.8	–	15.5
Mass (t / %)	150.3 / 100	46.8 / 31	29.7 / 20	76.5 / 51	73.8 / 49	
$^{(1)}$Rate (t/ha)	73.3	22.9	14.5	37.3	36.0	
Areas affected (m^2)	19625	638	237	875	20 500	
$^{(2)}$Rate (t/ha)	76.7	733.5	1253.2	874.3	36.0	

$^{(1)}$Calculated for the entire area of the measurement subcatchment, 20 500 m^2;

$^{(2)}$Calculated for areas affected by erosion or deposition.

lower field boundary was 76.5 t or 51% of the total amount of mobilized sediment (150.3 t). Of this, only 29.7 t (20% of total eroded volume) was redeposited along the lower field boundary, but the rate of the associated aggradation for this limited area above the plough terrace is very significant (Table 1), nearly 10 cm of sediments were deposited on average.

Another 31% of mobilized sediment (46.8 t) was redeposited within the field in a few prominent linear zones oriented transversally to the slope gradient and on a relatively larger rhombic-planform fan in the middle part of slope (Fig. 1(b)). It is important to note that two of the linear depositional zones stretched along topographic contour lines 235 m and 242 m are located below slope sections where practically no measurable rills were observed. That indicates that sheet erosion by non-concentrated flow also played substantial role in sediment redistribution during that rainfall event. Therefore, our estimates of erosion are most likely below the real volumes of eroded soil due to neglect of the contribution of sheet wash. Linearity of the within-field deposition zones and the short distance between the zones suggest that redeposition was associated with sediment concentration reaching critical values exceeding the transport capacity simultaneously in numerous parallel rills with similar flow discharges (or in sheet flow uniformly distributed across the slope surface). That is supported by the observed parallel rill network pattern without significant flow concentration or dispersal (Fig. 1(b)). The only exception is the rhombic-planform fan in the middle part of slope, which is probably located at a microtopographic depression caused by the harrowing tractor turn or other effects of cultivation operations. The rill network density notably increases downslope, reflecting higher erosion rates with increased slope gradient and overland flow.

Comparison of field estimates and simulations from the erosion model showed that the relatively moderate magnitude rainstorm event caused soil redistribution rates exceeding the modelled average annual figure by more than twice (Table 1). It is important to note that according to the available 100-year long meteorological observations, rainstorms with precipitation totals of around 20 mm occur in the Kursk Region 2–3 times per year during the June–August period.

Study site 2

Although measurements of sediment deposition in the dry valley bottom were reasonably detailed, it was impossible due to time and labour limitations to carry out measurements of fresh sediment deposition in the reservoir (Fig. 1(c)). In addition, as we undertook our measurements soon after the rainstorm, some sediment still remained suspended in the reservoir water. Therefore, it has been decided to calculate sediment deposition in the reservoir simply by taking the same average deposition thickness as measured for the valley bottom (Table 2). The reservoir is separated from the lower valley reach by a closed earthen dam. No traces of overspill have been observed during our field observations, thus we can consider the event-based sediment budget as closed, without any sediment export beyond the reservoir.

Two components of the catchment sediment budget remain unaccounted for in our measurements of sediment deposition, namely within-field redeposition (except for the deposition zone along the lower field boundary plough terrace) and deposition on grassed, steep dry valley sides. However, having conducted a detailed field survey of the entire catchment we can argue that both are negligible. Noticeable sediment bodies on valley sides have not been found. Sediment redeposition within the field was limited to thin layers accumulated in bottoms of larger rills and ephemeral gullies during the flow recession. No measurable deposition features similar to those found at study site 1 (Fig. 1(b)) were observed. It is therefore certain that the error term associated with these two components of the catchment sediment budget does not exceed 10% and the total erosion from the cultivated catchment slope can be reliably reconstructed by summing up the measured deposition volumes with correction for different bulk densities of the eroded plough layer and deposited sediment.

Table 2 shows that the significant rainstorm magnitude and intensity (40 mm in 1 hour, of which about 30 mm in approx. 0.5 hour according to our direct observations) caused severe erosion on the studied field and substantial sediment delivery into the adjacent valley bottom. SDR into the valley bottom was as high as 71% (including 347 t deposited in fans, 1414 t on the dry

Table 2 Results of direct measurements of deposition and reconstruction of erosion at study field 2 compared with average annual soil loss rate calculated by the erosion model. Bulk density of recently harrowed topsoil layer estimated as 1000 kg/m^3, and bulk density of freshly deposited sediment as 1300 kg/m^3, based on sample analysis.

	Area (m^2)	Average depth (m)	Volume (m^3) / Mass (t) / %	Rate (t/ha)
Sediment deposition in the reservoir (suggested as equal by layer to the dry valley bottom aggradation)	14 320	0.04	573 / 745 / 21	520.0
The dry valley bottom aggradation	27 210	0.04	1088 / 1414 / 40	520.0
Fans at the dry valley side bases	1 442	0.15	267 / 347 / 10	2406.4
Fans in grassed buffer strip between the cultivated field lower boundary and the dry valley side upper break	1 702	0.10	117 / 152 / 4	893.1
Within-field deposition zone along the lower field boundary	10 070	0.10	653 / 849 / 25	843.1
Total deposition (with reservoir)	–	–	2698 / 3507 / 100	–
Total erosion (reconstructed from deposition volumes corrected for lower bulk density of recently harrowed topsoil)	600 000	0.006	3507 /3507 / 100	58.5
Resulting soil loss from the field (total erosion minus within-field deposition)	600 000	0.004	- / 2658 / 75	44.3
Average annual soil loss rate calculated by the model (t/ha/year)				14.0

valley bottom itself and 745 t of supposed deposition in the reservoir). Such a high sediment delivery into the valley bottom is associated with numerous flow-concentrating slope depressions on the cultivated slope surface (Figs 1(c), 2) in which overflows through the lower field boundary plough terrace took place during the extreme runoff event. In contrast, below divergent slope segments (Figs 1(c), 2) most of the eroded sediment remained redeposited immediately above the plough terrace or within the grassed buffer strip.

Comparison of the event-based soil loss measurement with the average annual erosion rate estimated by the model shows that the observed extreme event sediment redistribution rates exceeded modelled rates from three "normal" years. Available meteorological data suggest that rainstorms with precipitation totals exceeding 40 mm occur in the Kursk Region on average once every 4–5 years, though such a relatively high maximum intensity (about 1 mm/min during the rainstorm core passage) may be observed less frequently.

Study site 3

Unlike the first two study sites, the observed spatial distribution of erosion rills on the slope was very non-uniform. Most erosion occurred in the bottoms of linear slope depressions where large rill systems were developed. Intensively eroded areas occupied not more than 10% of the studied area, while the rest was only affected by localized sediment redistribution. Within-field redeposition was limited and mainly localized in two separated fans at the lower field boundary (75% of total within-field redeposition or 6% of total sediment mobilized from slope). Local SDR from the field boundary during the observed event was about 92%, giving the resulting event-scale soil loss from the entire studied area of 13.2 t/ha (Table 3). Such a high SDR can be explained by the fact that most of the sediment transport over the observed event was associated with concentrated flows in slope depressions, which were shown to cause increased sediment export from arable slopes (Belyaev *et al.*, 2005)

Evaluation of the event-scale ^{137}Cs budget was based on the relatively-uniform radionuclide concentration in the plough layer (average value for samples taken from uneroded points, 67.2 KBq/kg) and on sediment redeposited within the field (average value, 70.7 KBq/kg), suggesting that particle size sorting by overland flow was not significant during that particular event. That supported the initial visual observations showing that depositional bodies mainly consisted of rounded soil aggregates rather than individual mineral particles. In eroded parts of the slope significant differences of ^{137}Cs inventories were observed between visually uneroded harrowing ridges (average value, 20.0 KBq/m^2), visually eroded harrowing furrows (17.8 KBq/m^2), and rill bottoms (16.9 KBq/m^2). Total ^{137}Cs loss from the field was calculated by multiplying the respective relative inventory losses by the areas occupied by rills and the areas of rill microcatchments from which sheet erosion-mobilized sediment was further transported by concentrated flows in rills. It was assumed that in areas disconnected from rill systems, soil particles mobilized by non-concentrated overland flow were rapidly redeposited. An important limitation of the ^{137}Cs event-based budget is that it was not possible to estimate deposition, because significantly higher isotope concentrations in the plough layer within the main depositional zone along the lower field boundary are associated with long-term deposition rather than with this single event. Hence deposition was not accounted for in the resulting figure of soil erosion over the observed event (19.9 t/ha, Table 3). That may partly explain the difference compared to the measured value of soil loss from the field (13.2 t/ha, Table 3). On the other hand, we know that direct measurements of rill volumes cannot account for sheet wash in rill microcatchments, as shown by the study site 1 example.

Table 3 Results of direct measurement of erosion and deposition at the study field 3 compared with average annual soil loss rate calculated by the ^{137}Cs technique and the erosion model.

	Sediment redistribution during the observed rainstorm event						Long-term average annual soil loss rate (t/ha/year)	
	Directly measured					Erosion calculated from the event-scale ^{137}Cs budget (t/ha)		
	Erosion	Deposition			Resulting soil loss from the field		Calculated by the ^{137}Cs method	Calculated by the model
		Within the field	Along the lower field boundary	Total deposition				
Volume (m^3)	220.5	3.9	9.7	13.6	–	–	14.8	21.6
Mass (t / %)	220.5 / 100	5.1 / 2	12.6 / 6	17.7 / 8	202.8 / 92	306.8		
(1)Rate (t/ha)	14.3	0.3	0.8	1.1	13.2	19.9		
Areas affected (m^2)	122 080	1 437	1 755	3 192	154 000	154 000		
(2)Rate (t/ha)	18.1	35.5	71.8	55.5	–	–		

(1)Calculated for the entire area of the measurement subcatchment, 154 000 m^2;

(2)Calculated for areas affected by erosion or deposition.

Average annual soil loss rate from the field from the ^{137}Cs transect data for 1986–2003 was estimated using the simple mass-balance model (Walling & Quine, 1990) modified by M. V. Markelov to account for loss of some fresh fallout isotope by erosion prior to first tillage mixing (i.e. assuming its exponential depth distribution during the first year iteration). Comparison of the long-term average annual soil loss rates estimated from the ^{137}Cs data and from the model shows differences that can most likely be explained by the fact that the former approach accounted for certain soil redeposition within the field along its lower boundary. However, generally the rates obtained are comparable, and the long-term average erosion rate estimated for the entire period of cultivation from the soil profile comparison along the same transect was 14.7 t/ha/year (Belyaev *et al.*, 2007), supporting the general validity of the figure obtained. Comparison of these values with the event-based soil loss measurement shows that the approx. 20 mm rainstorm (commonly taking place at least once per year) indeed performed about the entire average annual erosional work on the studied field.

DISCUSSION

Table 4 provides a summary of soil loss directly measured at the event timescale and estimated long-term averages for the three study sites. Following the above description of results, it is clear that for all three sites individual rainstorm events make substantial contributions to the average annual erosion rates. Unfortunately, such direct observations are generally rare, but there is one other reported case of a 20 mm per 20 minute rain causing soil loss of about 50 t/ha from a 400 m long slope also located relatively close to Kursk City. This value is comparable with our case 2, where rainfall intensities had approx. 30 mm in 30 min characteristics, and similar soil loss was observed. At the same time, long-term monitoring undertaken by scientists from Kursk at the experimental catchments located approximately between the case study sites 1 and 2, showed that erosion rates during snowmelt periods are more than three times lower than our average annual values and vary within a range of 2.8–3.7 t/ha from year to year (Zdorovcev & Doschechkina, 2003). This is in contradiction with the widely accepted opinion that snowmelt runoff erosion plays the main role in soil erosion on arable fields of this part of Russia. There is obviously a need for more clarifying research in this direction.

Table 4 Comparison of directly measured event-based and average annual soil loss for the study sites and characteristics of magnitude and frequency of corresponding rainstorm events, based on direct observations and available meteorological records.

Study site	Event magnitude / frequency	Directly measured soil loss from the field during individual event (t/ha) / (% of averages)	Soil loss during individual event calculated from the event-scale ^{137}Cs budget (t/ha) / (% of averages)	Calculated by the ^{137}Cs method (t/ha/year)	Calculated by the model (t/ha/year)
1	20 mm / 2–3 per year	36.0 / 232	–	–	15.5
2	40 mm / once per 4–5 years	44.3 / 316	–	–	14.0
3	20 mm / 2–3 per year	13.2 / 61–89	19.9 / 92–134	14.8	21.6

CONCLUSION

The data show that even a relatively moderate rainstorm (close to the average annual rainstorm) can, alone, be responsible for soil loss equivalent to, or even exceeding, the average annual value, providing that it occurs when the cultivated field surface is in the most vulnerable condition. Further research should test the common assumption that snowmelt runoff erosion makes the most important contribution to total soil loss from arable fields in this part of Russia. This information should be taken into account when planning soil-protective crop rotations. In the case of central European Russia, it is most important to avoid leaving fields fallow for long periods of time, especially in July–August when most of the extreme rainstorms occur. We believe that the approach applied in this study has proved to be useful and it is planned to apply it to collect more information on the temporal variability and contribution of extreme events to the average soil redistribution rates on arable slopes for different configurations and under different crop rotations.

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