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Post-fallout redistribution of Chernobyl-derived caesium-137 in small catchments within the Lokna River basin, Russia

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Abstract Detailed investigations of the redistribution and accumulation of Chernobyl-derived ^{137}Cs in small drainage basins were conducted using a sediment budget approach in the Lokna River basin, 250 km south of Moscow. Two small catchments were chosen for the detailed study: the Chasovenkov Verh Balka basin with an area of 42.1 km^2 and the Lapki Balka basin with an area of 2.18 km^2. The results show that 12 years after the Chernobyl accident, there has been a significant decrease in the ^{137}Cs content on cultivated slopes and a substantial increase in the ^{137}Cs content at depositional sites along flow pathways from the cultivated slopes to river channels.

INTRODUCTION

Vast areas of Europe were highly contaminated by radionuclides after the Chernobyl Power Plant accident in 1986. A few areas of the Russian Plain show the highest level of the contamination (Vakulovski *et al.*, 1998). Erosion and depositional processes are major factors of the post-fallout redistribution of ^{137}Cs in agricultural areas, because the radionuclide is strongly fixed by clay particles immediately after fallout (Frissel & Pennders, 1983) and its subsequent transport occurs in association with soil or sediment particles. This feature makes ^{137}Cs a good tool for evaluating erosion and deposition rates (Walling & Quine, 1991; Walling *et al.*, 1996). Horizontal redistribution of the Chernobyl-derived ^{137}Cs is a serious environmental problem in areas with a high level of radionuclide contamination. This contribution examines aspects of ^{137}Cs transport within small agricultural catchments of the Lokna River basin, in the Tula Region, Russia.

STUDY AREA

The Lokna River basin is located 250 km south of Moscow and 650 km northeast of Chernobyl. Radionuclide levels from the Chernobyl fallout in excess of 200 kBq m^{-2}

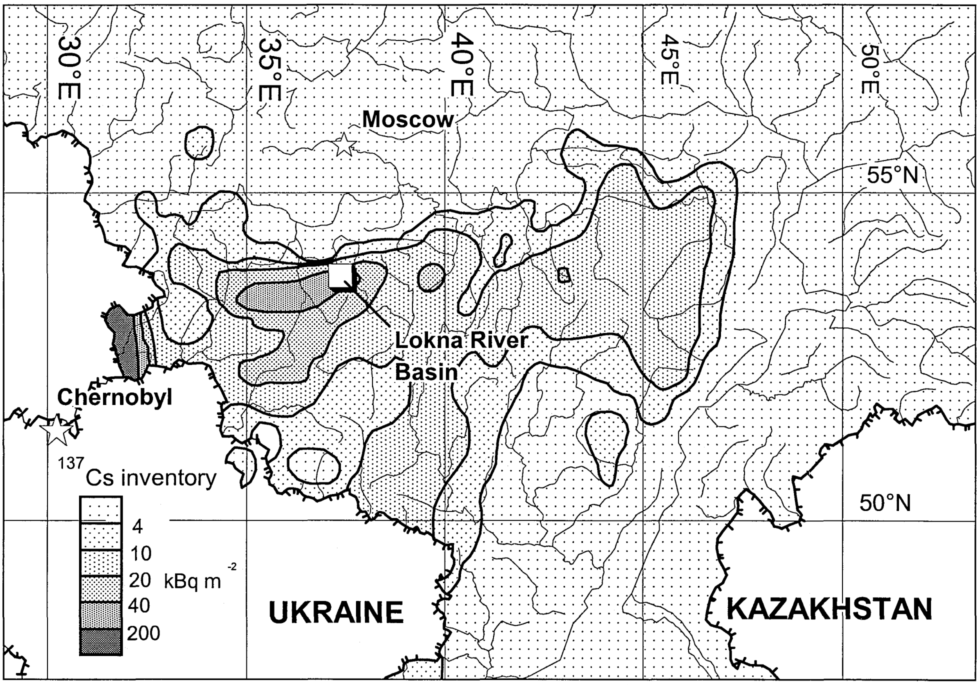

Fig. 1 Location of the Lokna River basin within the area of ^{137}Cs contamination in central Russia.

were recorded by airborne gamma spectrometry surveys immediately after the Chernobyl accident (Fig. 1). Because bomb-derived ^{137}Cs inventories are almost two orders of magnitude lower, they are unlikely to have significant influence on the current spatial distribution of the ^{137}Cs within the study area. The topography of the Lokna River basin is dominated by a relatively flat interfluve area surrounded by gentle slopes, which have been dissected by different types of balka or ephemeral valleys (Golosov *et al.*, 1998). Sediment and sediment-associated radionuclides are mostly transported from cultivated slopes to balka valleys and then to the river channel. Four major types of balka valley with different types of sediment transport have been identified within the Lokna basin. Their characteristics were described by Golosov *et al.* (1998).

METHOD

Two balka catchments (Chasovenkov Verh Balka and Lapki Balka) were chosen as key areas. The balka valleys were studied in detail and then representative slope catchments (Fig. 2) were chosen for careful investigation within each balka basin. Field work was conducted in 1997 and 1998. Large-scale geomorphological maps, made for each catchment, were used for sampling and measurement programmes. Between 10 and 25 points of the ^{137}Cs content were made within each geomorphological unit. In addition, a detailed differentiated geodetic positional system (DGPS)-based topographical survey was carried out to provide a catchment

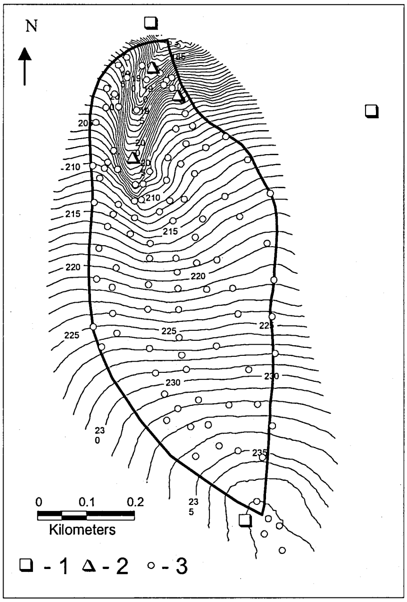

Fig. 2 Example of representative catchment: topographical plan of left tributary of the Lapki Balka basin (1: reference pits; 2: depositional pits; 3: sampling points).

topographic map, to determine the areal extent of various geomorphological units and the locations of sampling and measurement sites. Due to the initial variability of the Chernobyl radionuclide fallout (Golosov *et al.*, 1999), reference sites were chosen at different sites within the key areas. Reference sites were located on relatively flat uncultivated surfaces without erosion and sedimentation. Soil and sediment cores were collected using metal corers. Soil cores from cultivated fields were collected to depths in excess of 40 cm. Most soil cores were bulked, but some samples were split from 0–30 and 30–40 cm to determine the background ^{137}Cs level in uncultivated soil horizons. Depth incremental cores were collected from each geomorphological unit in depositional areas. In addition, some bulk samples were taken from different parts of the bottoms and sides of the valley. In addition, sediment samples were taken for radionuclide and grain size analysis from ephemeral flows during snowmelt events at different sites located along the bottom of the Chasovenkov Verh Balka. Two different approaches were used for estimation of depositional rates. The position of the level with peak activity was used to estimate the depth of the 1986 surface (Walling & He, 1992) for pits where incremental cores were taken. For the bulk samples the total inventory of depositional core is compared with a reference value representing the local fallout inventory. The value of "excess" inventory is assumed to reflect the deposition of sediment derived from the upstream catchment (Walling & Bradley, 1989).

All soil samples were dried and sieved to <2 mm prior to laboratory analysis of ^{137}Cs using gamma spectrometry with an HPGe coaxial detector calibrated with Standard Reference Materials. Count times were sufficient to provide a typical analytical precision of ±4–5%. The particle size composition of some sediment cores was determined using Malvern Mastersizer and the standard pipette method.

The intensity of soil erosion caused by rainstorms was estimated using a modified version of USLE (Larionov, 1993). The State Hydrological Institute model (Larionov, 1993) was applied to estimate erosion rates during the snowmelt period. The results of calculations are included in Tables 1–4.

RESULTS AND DISCUSSION

Within-field ^{137}Cs redistribution and storage

Various factors influence the spatial pattern of ^{137}Cs within cultivated fields: initial fallout trend, tillage erosion, water erosion and local wind erosion. It was established, that the initial levels of ^{137}Cs in fallout increased from the south to the north with a maximum concentration along the Lokna River valley (Golosov *et al.*, 1999; Walling *et al.*, in press). The Lapki Balka basin has soil erosion rates less than 20 t ha^{-1} year^{-1}, and it was not possible to detect major variations in ^{137}Cs contents between the upper and middle parts of cultivated slopes within Field 1, which are located in the upper part of the Lapki Balka basin. However, a deposition zone at the base of a slope was identified (Table 1). In contrast, the ^{137}Cs levels decrease from the upper to the bottom parts of Field 2, located in the mouth of the Lapki Balka basin, despite the increase in the initial (reference) fallout concentration from the slope bottom to the interfluve (Table 1). Predominant rill erosion along the hollow bottoms within Field 2 is the main reason for ^{137}Cs losses in the middle and bottom parts of the cultivated slope.

Soil losses from some parts of cultivated slopes of the Chasovenkov Verh Balka basin exceed 20 t ha^{-1} year^{-1}. Furthermore, the effect of local sediment transport from upper slope fields along a road combined with local wind erosion transforms the ^{137}Cs distribution patterns within the upper parts of Fields 1 and 2. As a result, major differences between the upper, middle and bottom parts of cultivated slopes were identified (Table 2). It is evident that the areas of maximum ^{137}Cs loss do not coincide with slopes with maximum gradients and this can be explained by sediment deposition at the bottom of the slope (Field 1). The absence of the ^{137}Cs deposition at the base of Fields 1 and 2 results from the lack of a tillage dam at the border between the cultivated and uncultivated parts of the slopes. A tillage dam usually occurs at permanent borders between cultivated and uncultivated parts of a slope.

Table 1 Mean values of Chernobyl-derived caesium-137 content within different parts of cultivated fields, Lapki Balka basin.

Part of slope	Gradient	Erosion rate (Mg ha^{-1} year^{-1})	Field 1: ^{137}Cs inventory (kBq m^{-2})	Reference inventory (kBq m^{-2})	Field 2: ^{137}Cs inventory (kBq m^{-2})	Reference inventory (kBq m^{-2})
Interfluve	0–0.01	0–1	320 ± 30	324	561 ± 91	563
Upper part	0.02–0.04	1–5	388 ± 59	374	426 ± 49	516
Middle part	0.03–0.05	5–10	360 ± 77	374	374 ± 58	470
Bottom part	0.05–0.07	10–20	351 ± 52	374	403 ± 30	424
Base part			572 ± 122	424	no data	

Table 2 Mean values of Chernobyl-derived caesium-137 content within different parts of cultivated fields, Chasovenkov Verh Balka basin (reference for entire area: 353 kBq m^{-2}).

Part of slope	Field 1: Gradient	Erosion rate (t ha^{-1} $year^{-1}$)	^{137}Cs inventory (kBq m^{-2})	Field 2: Gradient	Erosion rate (t ha^{-1} $year^{-1}$)	^{137}Cs inventory (kBq m^{-2})
Upper part	0.06–0.08	0–10	369 ± 66	0.05–0.09	0–10	362 ± 46
Middle part	0.10–0.14	10–20	301 ± 76	0.09–0.10	10–20	349 ± 73
Bottom part	0.13–0.16	20–30	353 ± 57	0.07–0.09	20–30	310 ± 69

^{137}Cs transport and deposition within balka valleys

Most of ^{137}Cs delivered from cultivated slopes reaches balka bottoms. However, some sediments and sediment-associated ^{137}Cs are re-deposited on the sides of balka valleys. According to field observations, two types of depositional areas can be identified on the valley sides. First, an uncultivated hollow bottom serves as a permanent pathway for water and sediment flow from tillage to a valley bottom. Thus some sediments are re-deposited during each flow event and mostly at the border between cultivated and uncultivated parts of a hollow bottom and on a hollow fan within a valley bottom. Other deposition areas on valley slopes cannot be identified easily. Generally they can be assessed using indirect measures (differences in vegetation type, slope configuration). Usually deposition rates vary considerably within such slopes and a single measurement of the ^{137}Cs content cannot identify the actual radionuclide deposition within this geomorphological unit. Therefore, the results of the study show that about 8–12% of total sediment loss and sediment-associated ^{137}Cs redeposition occurs on balka valley sides.

Sediment and associated radionuclide transport capacity at balka bottoms depends on various factors such as gradient of balka bottom, cross-sectional profile, sediment concentration in a permanent flow and the type of flow event. The transport capacity of a permanent flow can be determined as (Zamarin, 1951):

$$R = 0.022 \cdot Q\left(\frac{U}{w}\right)^{1.5}\sqrt{HI} \qquad (1)$$

where R is the transport capacity of flow (kg s^{-1}); Q is water discharge (m^3 s^{-1}); U is flow velocity (m s^{-1}); w is fall velocity (m s^{-1}); H is flow depth (m); and I is the gradient.

However, it is necessary to use some additional parameters for the evaluation of sediment transport along balka bottoms. Equation (1) can be applied directly to calculate the transport capacity within incised channels, which are typical for a transit section in the balka bottom. A roughness coefficient should be included in equation (1) if it is used for transport capacity determination of a vegetated balka bottom.

The permanent flows can be divided into two groups depending on season. Flows during a snowmelt are characterized by relatively low sediment concentrations, often less than their transport capacity. Snow accumulated within a balka bottom serves to filter sediments. Therefore, the sediment accumulation depends on the density and depth of snow cover until flow has cut through the snow and ice cover. Permanent flows produced by high intensity rainstorms are characterized by high irregularity of water and sediment discharges along a balka bottom and depend on crop rotation of adjacent cultivated slopes. Generally, about 70–80% of sediments, which are delivered from the cultivated slopes to balka bottoms with gradient <0.02 are re-deposited in fans located at mouths of the balka's tributaries with gradients >0.02 or at hollow mouths. Accordingly, these areas are characterized by extremely high accumulation rates and, as a consequence, by very high ^{137}Cs concentrations.

The combination of these factors causes the high variability of sediment and associated radionuclide accumulation at balka bottoms (Golosov *et al.*, 1999). However, the gradient of balka bottoms and the roughness coefficient are the major parameters to identify balka bottom sections with different sedimentation rates. In our case, it is possible to choose the different parts within key balka bottoms, which are characterized by different sediment and ^{137}Cs deposition rates, which was established using the shape of ^{137}Cs depth profile (Walling & Bradley, 1989) (Table 3).

Table 3 Mean sediment deposition and ^{137}Cs deposition rates in different section of key balka bottoms.

Section of the valley bottom	Lapki Balka: Average slope	Sediment deposition rate (g cm^{-2} year^{-1})	^{137}Cs deposition rate (kBq m^{-2} year^{-1})	Chasovenkov Verh Balka: Average slope	Sediment deposition rate (g cm^{-2} year^{-1})	^{137}Cs deposition rate (kBq m^{-2} year^{-1})
Transit–accumulation	-	-	-	0.0054	+0.09	+11.0
Accumulation	0.024	+0.12	+19.5	0.0024	+0.18	+28.0
Transit	0.027	+0.06	+8.6	0.0038	+0.12	+18.5

Assessment of ^{137}Cs fallout redistribution within small catchments

As previous studies demonstrate, balka bottoms serve as a sink for storage of sediments derived from cultivated slopes (Golosov *et al.*, 1992; Golosov, 1998). Typically, about 7–10% of sediments eroded within balka catchments are delivered to river channels. A preliminary sediment budget calculated for the Chasovenkov Verh Balka basin shows that only 7% of the sediments enter the Lokna River channel (Golosov *et al.*, 1998). Because deposition is a selective process and it increases the percentage of small particles (particularly silt and clay) in a sediment load composition, there is an increased concentration of ^{137}Cs in transported sediments compared to original soils. Grain-size analysis of flow samples taken during a period of snowmelt along the Chasovenkov Verh Balka confirms the flow enrichment by silt and clay down to the mouth of the balka (Fig. 3). The comparison of the grain-size composition of sediments taken from uncultivated depositional balka sides and from the balka bottom with cultivated slope soils shows similar results (Fig. 4). Therefore, this should be taken into consideration when using ^{137}Cs measurements of bulk cores to estimate the deposition rate. The ^{137}Cs and sediment export from a small catchment can be estimated using two different methods depending on the available information. A standard sediment budget approach can be used to estimate ^{137}Cs export:

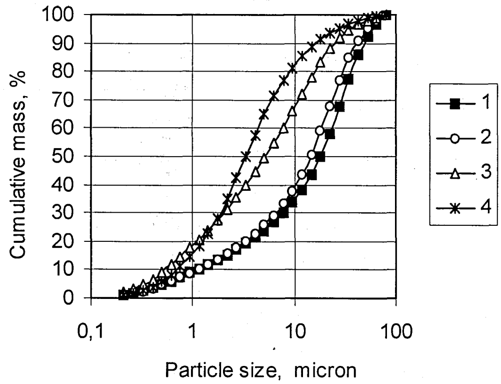

Fig. 3 Grain size composition of sediments, taken from permanent flow in the Chasovenkov Verh Balka bottom. (Core was taken – 1: 4.5 km from the balka mouth, accumulation section; 2: 3.9 km from the balka mouth, accumulation section; 3: 2.5 km from the balka mouth, transit section; 4: conjunction zone with the Lokna River channel.)

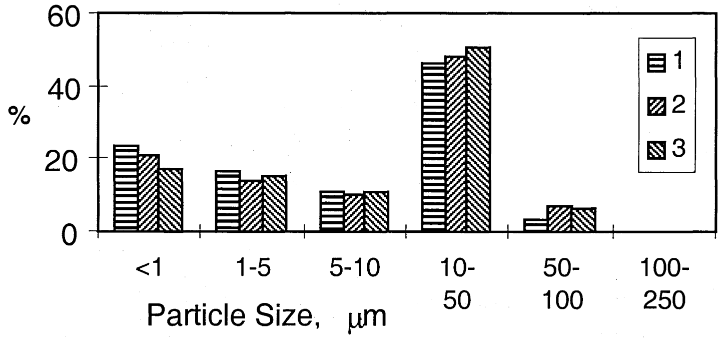

Fig. 4 Mean grain size composition of cultivated soil deposit from different geomorphological units: Lapki Balka basin (1: cultivated soil; 2: uncultivated balka side with deposition; 3: flood plain in the balka bottom).

$$W_l(t) = \left[\sum_i^n R_e(t) S_e - \sum_i^n R_d(t) S_d \right] C_f(t) \tag{2}$$

where $W_l(t)$ (kBq year^{-1}) represents the total losses of ^{137}Cs from the catchment per year; S_e (m^2) and S_d (m^2) are areas of erosional and depositional geomorphological unit; $R_d(t)$ (g cm^{-2} year^{-1}) and $R_e(t)$ (g cm^{-2} year^{-1}) are the sediment accumulation rate and the erosion rate—parameter $R_e(t)$ was determined using an erosion model (Larionov, 1993); and $C_f(t)$ (kBq g^{-1}) is the ^{137}Cs content of transported sediments. Erosional and depositional units of the landscape were determined using DGPS survey of the catchment (for the depositional units) or from the erosion map (for the erosional units). For uncultivated units, $R_d(t)$ was calculated from the depth of sediments above the ^{137}Cs peak, which is assumed to correspond to ^{137}Cs fallout in 1986. For cultivated units, $R_d(t)$ was based on the depth to which ^{137}Cs extends below the plough depth.

Table 4 Caesium-137 and sediment export from the left lower tributary of the Lapki basin.

Geomorphological unit	Area (m^2)	Calculation of ^{137}Cs export using equation (3):				Calc. of sediment export using equation (2)
		Mean ^{137}Cs inventory* (kBq m^{-2})	^{137}Cs total content per unit (×10^3 kBq)	^{137}Cs reference inventory (kBq m^{-2})	^{137}Cs loss/gain (×10^3 kBq $year^{-1}$)	Sediment loss/gain (t $year^{-1}$)
Interfluve	16 800	320	5 380	324	–6.1	–0.3
Cultivated slope	230 800	365	84 240	374	–188.8	–157.8
Base of cultivated slope	3 000	572	1 710	424	+40.4	+28.9
Uncultivated balka sides without deposition	20 100	424	8 520	424	0	0
Hollows on balka sides with deposition	1 200	478	570	424	+5.9	+16.4
Balka bottom	6 200	616	3 820	424	+108.2	+67.6
Total	278 100	375	104 240		–40.4	–45.2

* All ^{137}Cs inventories have been corrected for radioactive decay to 1 June 1997.

The ^{137}Cs export from small catchments can be also estimated using the following equation:

$$W_l(t) = \left\{ \sum_i^n \frac{[L_e(t) - I(t)]}{T} S_e - \sum_i^n \frac{[L_d(t) - I(t)]}{T} S_d \right\} \alpha \tag{3}$$

where $L_e(t)$ and $L_d(t)$ (kBq m^{-2}) are the mean ^{137}Cs contents at the time of sampling for erosional and depositional units, respectively; $I(t)$ (kBq m^{-2}) is the initial (reference) input ^{137}Cs fallout corrected to the time of sampling; T (year) is the period that has elapsed between the time of sampling and 1986; and α is a dimensionless particle size and organic matter correction coefficient (He & Walling, 1996). Calculation of the ^{137}Cs export for the left lower tributary of the major Lapki Balka valley was made using both methods (Table 4). The mean caesium-137 content in sediments from the permanent flow is 1062 mBq g^{-1}; thus the total ^{137}Cs losses calculated by the sediment budget method (equation (2)) are 48×10^3 kBq $year^{-1}$. The particle size correction coefficient is 1.26 and the total ^{137}Cs losses estimated by the ^{137}Cs budget method are 50.9×10^3 kBq $year^{-1}$. Because these methods are independent, it is possible to assume that actual ^{137}Cs losses from a small catchment can be estimated using both methods.

CONCLUSION

The results of the study show that the most of the Chernobyl-derived ^{137}Cs is re-deposited within balka catchments in the Lokna River basin. The most significant accumulation of ^{137}Cs is observed within balka bottoms where 50–60% (Table 4) of sediments and associated ^{137}Cs are stored depending on bottom gradients (Table 3). Two different methods can be applied to evaluate the ^{137}Cs export from a small catchment and both methods provide similar results.

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